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Earl et al.

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(54) **HYDROGEN APPLICATIONS FOR TURBOEXPANDER MACHINES**

(71) Applicant: **Sapphire Technologies, Inc.**, Cerritos, CA (US)

(72) Inventors: **Jeffrey Earl**, Hermosa Beach, CA (US); **Freddie Sarhan**, Anaheim, CA (US); **Jeremy Liu**, Norwalk, CA (US)

(73) Assignee: **Sapphire Technologies, Inc.**, Cerritos, CA (US)

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F01D 15/10 (2006.01)
H02P 9/04 (2006.01)

(52) **U.S. Cl.**
CPC ***H02K 7/1823*** (2013.01); ***F01D 15/10*** (2013.01); ***H02P 9/04*** (2013.01); *F05D 2210/12* (2013.01); *F05D 2220/74* (2013.01); *F05D 2220/75* (2013.01); *F05D 2220/7642* (2013.01); *F05D 2270/061* (2013.01)

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See application file for complete search history.

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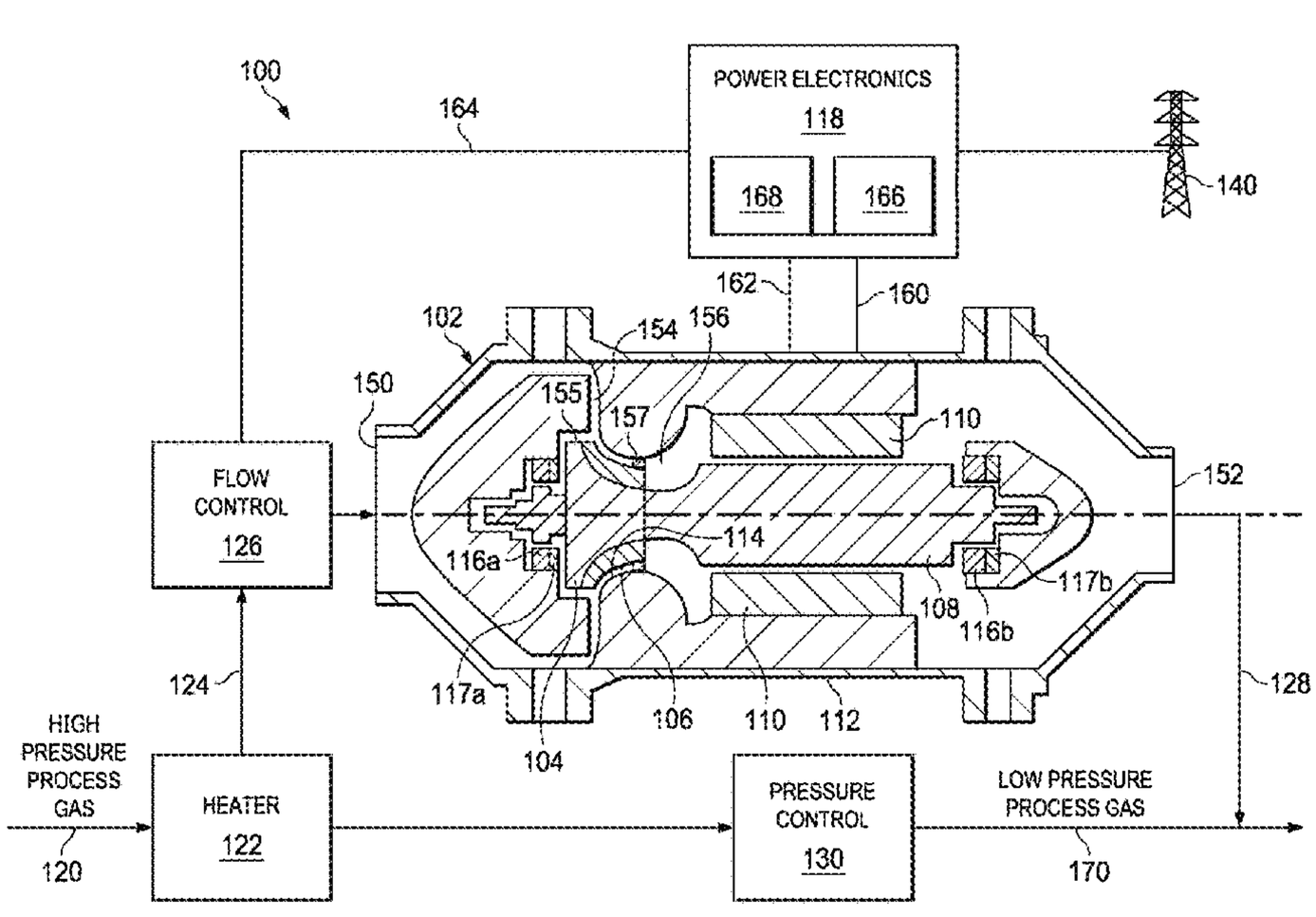
Primary Examiner — Joseph Ortega
(74) *Attorney, Agent, or Firm* — Fish & Richardson P.C.

(57) **ABSTRACT**

An apparatus includes an electric generator that includes a fluid inlet configured to receive hydrogen at a first pressure, a turbine wheel configured to expand the hydrogen and rotate in response to expansion of the hydrogen flowing into an inlet of the turbine wheel and out of the outlet of the turbine wheel, a rotor coupled to the turbine wheel and configured to rotate with the turbine wheel, a stationary stator, the electric generator to generate an alternating current upon rotation of the rotor within the stator, and a fluid outlet configured to output hydrogen at a second pressure less than the first pressure. The apparatus includes a power electronics system electrically connected to an electrical output of the electric generator and to receive alternating current from the electric generator. The power electronics can condition the generated electrical current to supply power to various types of loads.

19 Claims, 12 Drawing Sheets



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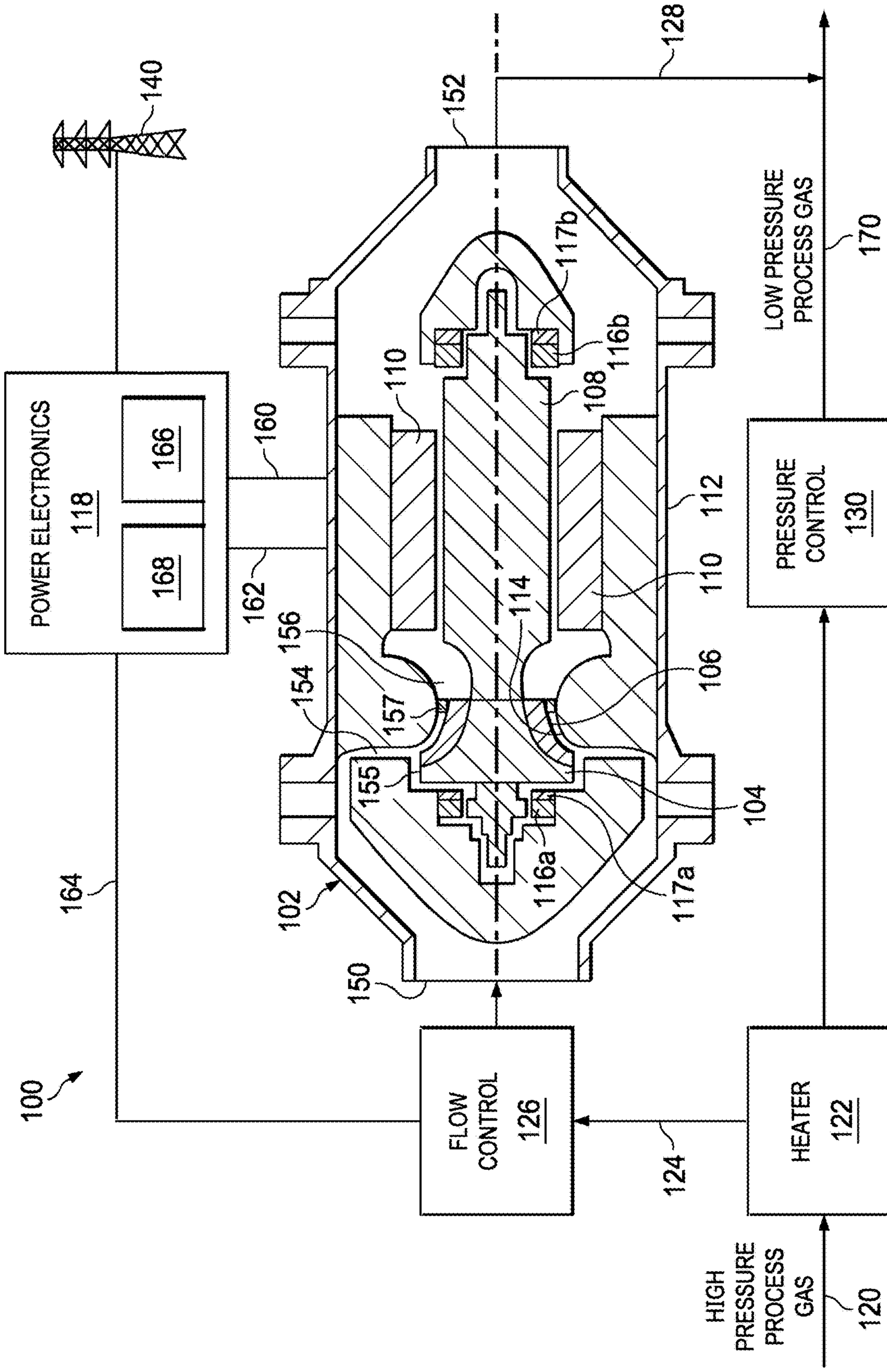
140
POWER ELECTRONICS
118
166
168
160
162
164
100
152
128
LOW PRESSURE
PROCESS GAS
170
117b
116b
110
108
112
114
156
154
157
106
155
104
116a
117a
102
150
PRESSURE
CONTROL
130
FLOW
CONTROL
126
124
HEATER
122
HIGH
PRESSURE
PROCESS
GAS
120

FIG. 1

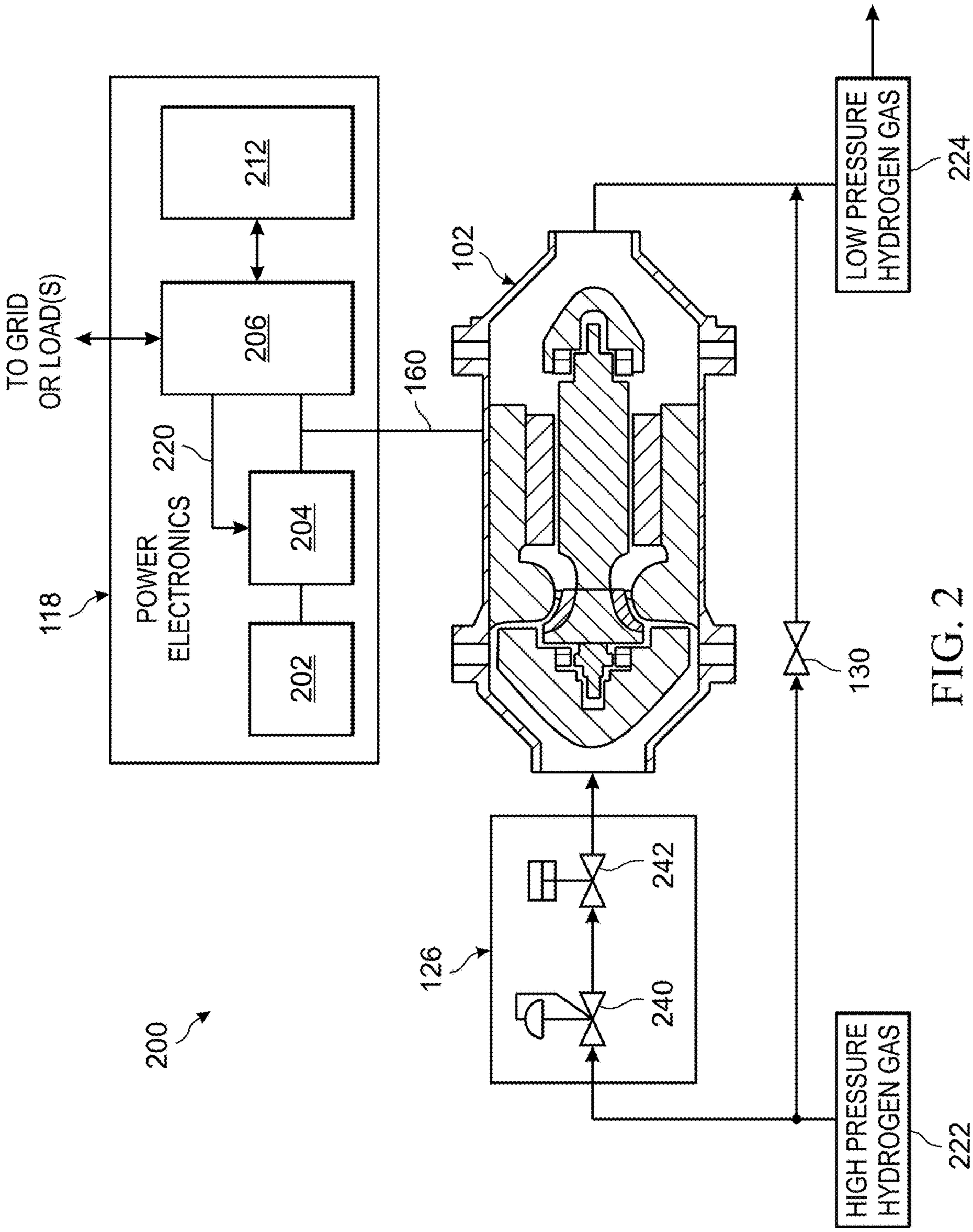
200
118
212
206
204
202
220
POWER ELECTRONICS
TO GRID OR LOAD(S)
160
102
126
242
240
130
224
LOW PRESSURE HYDROGEN GAS
222
HIGH PRESSURE HYDROGEN GAS

FIG. 2

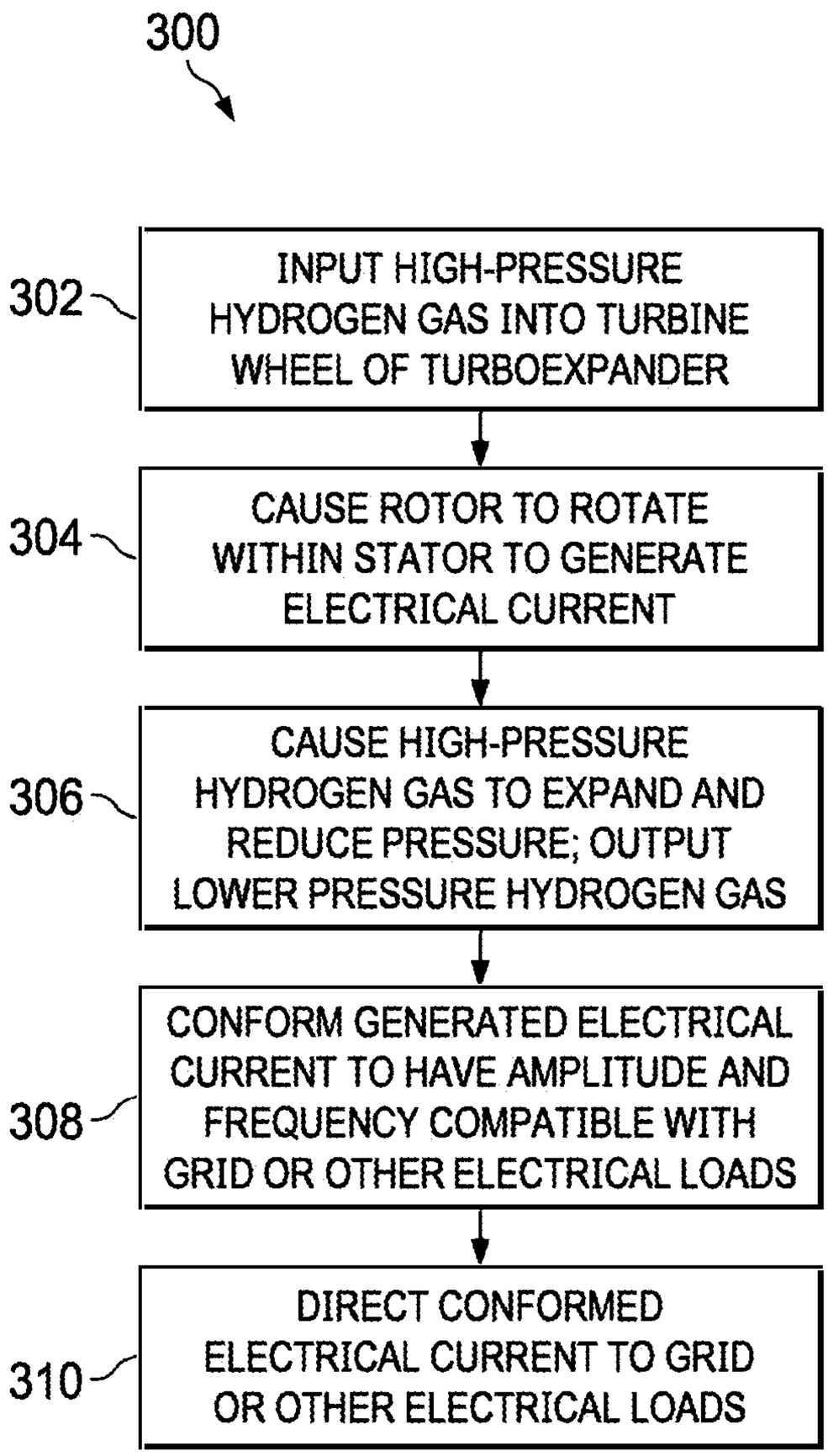
300
302
INPUT HIGH-PRESSURE HYDROGEN GAS INTO TURBINE WHEEL OF TURBOEXPANDER
304
CAUSE ROTOR TO ROTATE WITHIN STATOR TO GENERATE ELECTRICAL CURRENT
306
CAUSE HIGH-PRESSURE HYDROGEN GAS TO EXPAND AND REDUCE PRESSURE; OUTPUT LOWER PRESSURE HYDROGEN GAS
308
CONFORM GENERATED ELECTRICAL CURRENT TO HAVE AMPLITUDE AND FREQUENCY COMPATIBLE WITH GRID OR OTHER ELECTRICAL LOADS
310
DIRECT CONFORMED ELECTRICAL CURRENT TO GRID OR OTHER ELECTRICAL LOADS

FIG. 3

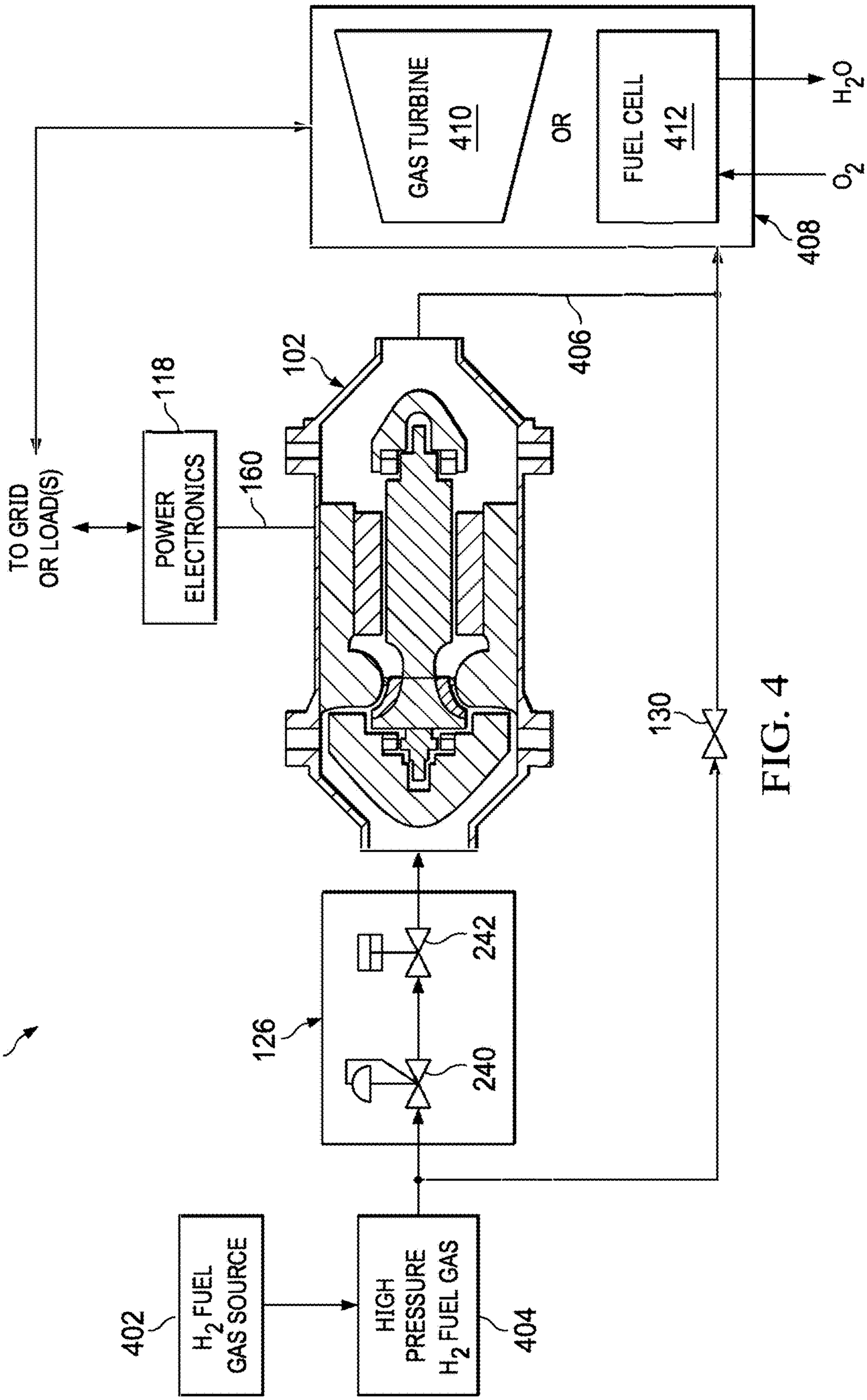
400
402
H_2 FUEL GAS SOURCE
404
HIGH PRESSURE H_2 FUEL GAS
126
240
242
130
406
102
118
TO GRID OR LOAD(S)
POWER ELECTRONICS
160
GAS TURBINE 410
OR
FUEL CELL 412
H_2O
O_2
408

FIG. 4

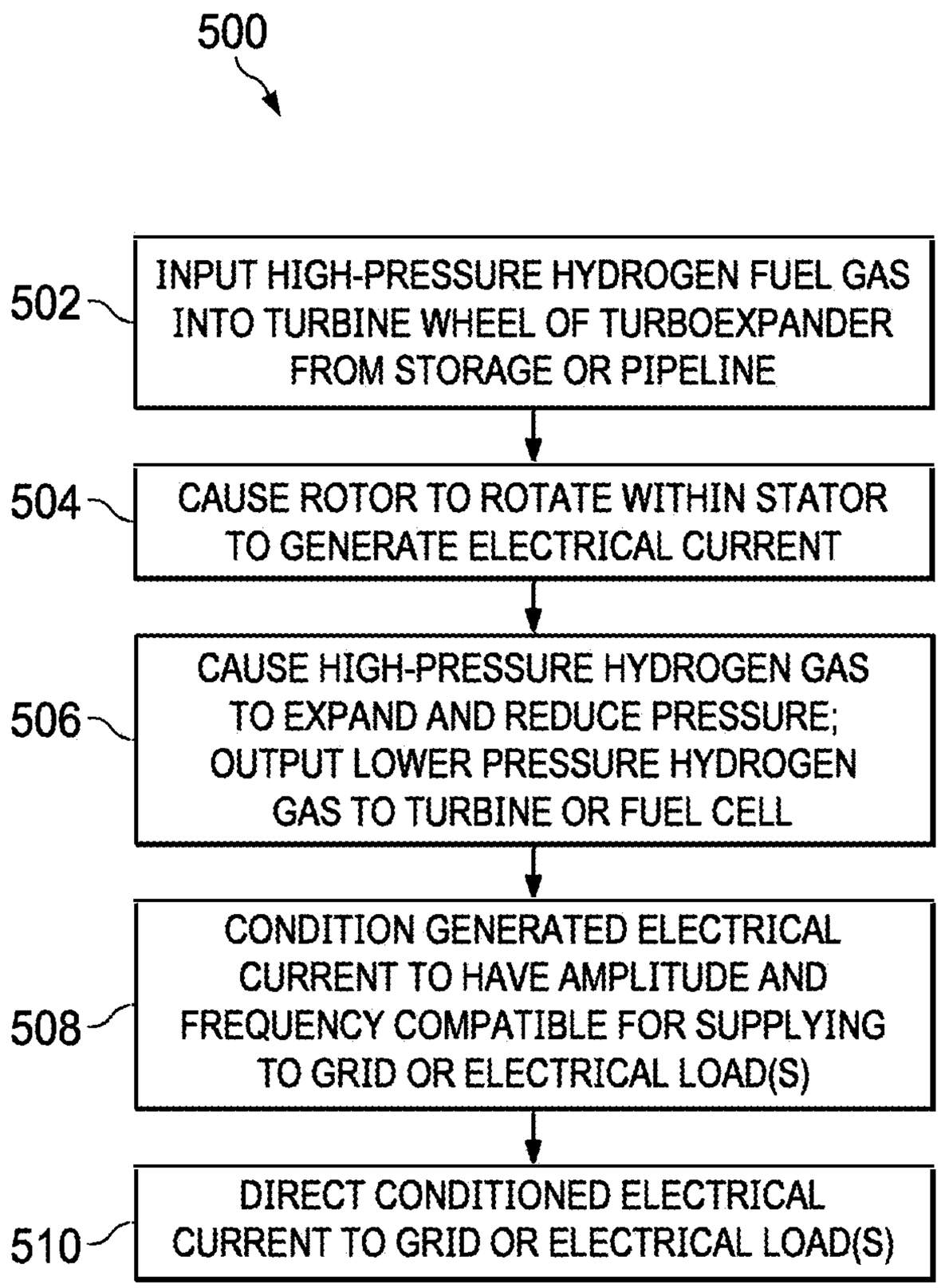
500
502
INPUT HIGH-PRESSURE HYDROGEN FUEL GAS INTO TURBINE WHEEL OF TURBOEXPANDER FROM STORAGE OR PIPELINE
504
CAUSE ROTOR TO ROTATE WITHIN STATOR TO GENERATE ELECTRICAL CURRENT
506
CAUSE HIGH-PRESSURE HYDROGEN GAS TO EXPAND AND REDUCE PRESSURE; OUTPUT LOWER PRESSURE HYDROGEN GAS TO TURBINE OR FUEL CELL
508
CONDITION GENERATED ELECTRICAL CURRENT TO HAVE AMPLITUDE AND FREQUENCY COMPATIBLE FOR SUPPLYING TO GRID OR ELECTRICAL LOAD(S)
510
DIRECT CONDITIONED ELECTRICAL CURRENT TO GRID OR ELECTRICAL LOAD(S)

FIG. 5

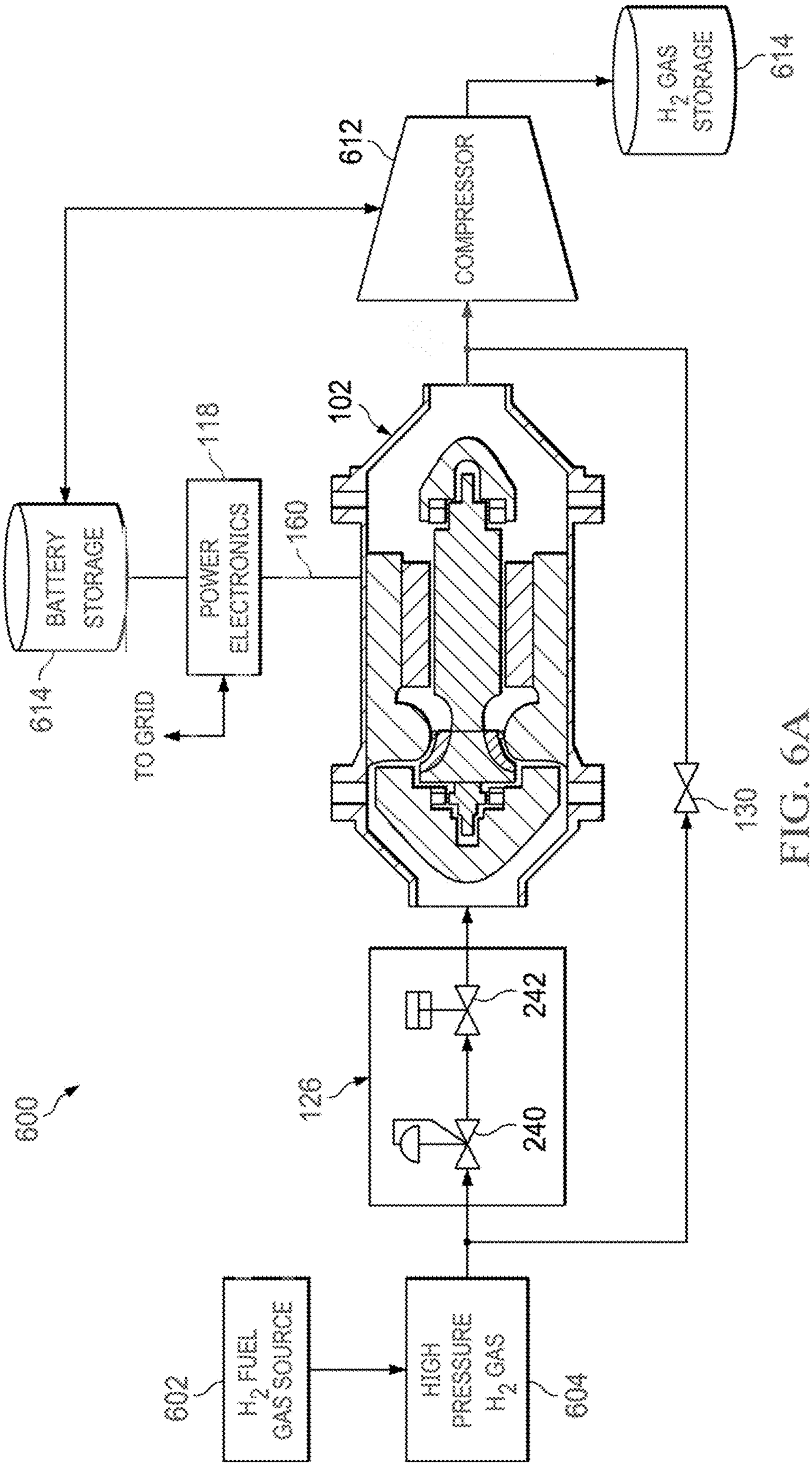
600
602
H_2 FUEL GAS SOURCE
604
HIGH PRESSURE H_2 GAS
126
240
242
102
612
COMPRESSOR
614
H_2 GAS STORAGE
118
POWER ELECTRONICS
160
614
BATTERY STORAGE
TO GRID
130

FIG. 6A

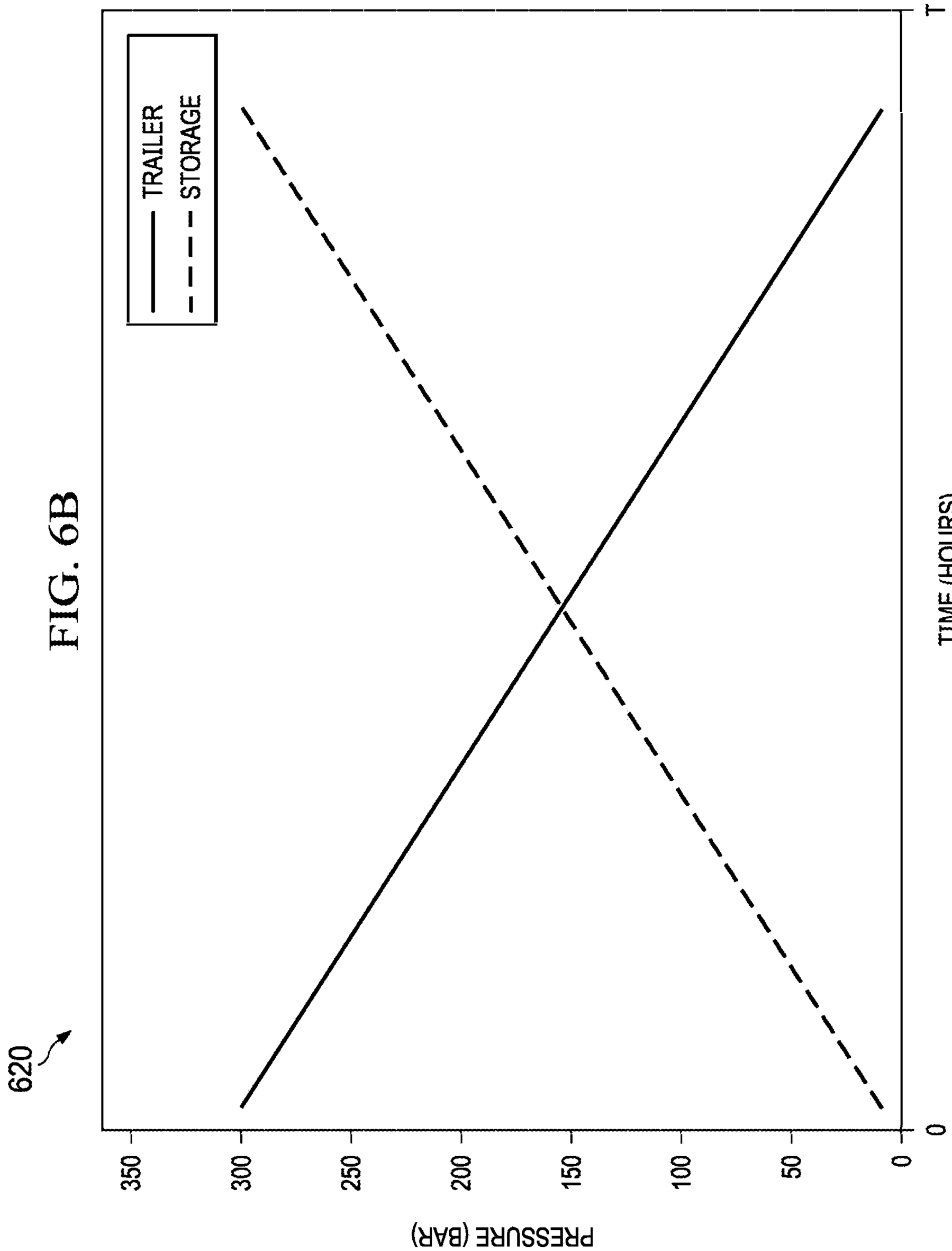
620
TRAILER
STORAGE
350
300
250
200
150
100
50
0
PRESSURE (BAR)
0
TIME (HOURS)

FIG. 6B

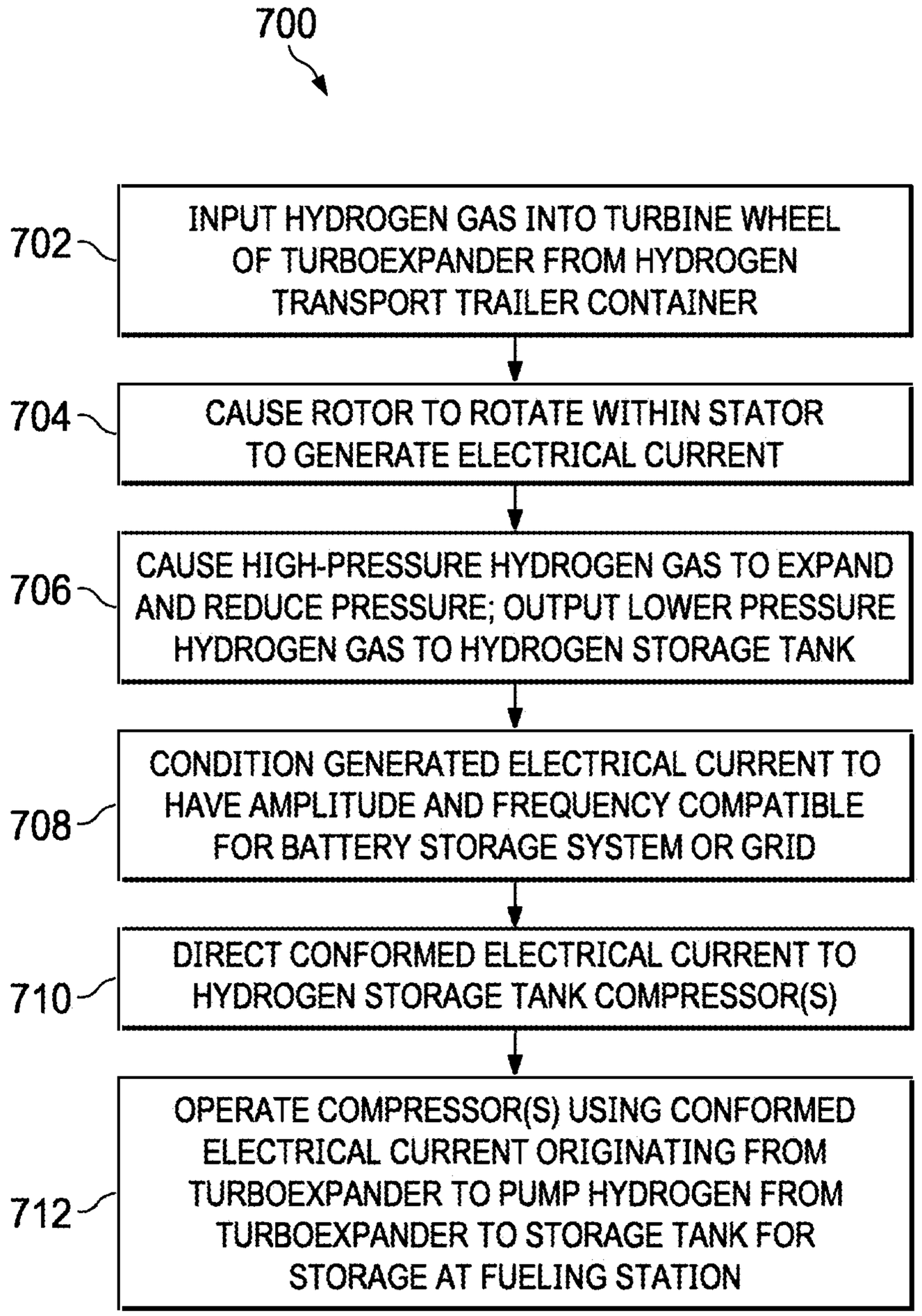
700
702
INPUT HYDROGEN GAS INTO TURBINE WHEEL OF TURBOEXPANDER FROM HYDROGEN TRANSPORT TRAILER CONTAINER
704
CAUSE ROTOR TO ROTATE WITHIN STATOR TO GENERATE ELECTRICAL CURRENT
706
CAUSE HIGH-PRESSURE HYDROGEN GAS TO EXPAND AND REDUCE PRESSURE; OUTPUT LOWER PRESSURE HYDROGEN GAS TO HYDROGEN STORAGE TANK
708
CONDITION GENERATED ELECTRICAL CURRENT TO HAVE AMPLITUDE AND FREQUENCY COMPATIBLE FOR BATTERY STORAGE SYSTEM OR GRID
710
DIRECT CONFORMED ELECTRICAL CURRENT TO HYDROGEN STORAGE TANK COMPRESSOR(S)
712
OPERATE COMPRESSOR(S) USING CONFORMED ELECTRICAL CURRENT ORIGINATING FROM TURBOEXPANDER TO PUMP HYDROGEN FROM TURBOEXPANDER TO STORAGE TANK FOR STORAGE AT FUELING STATION

FIG. 7

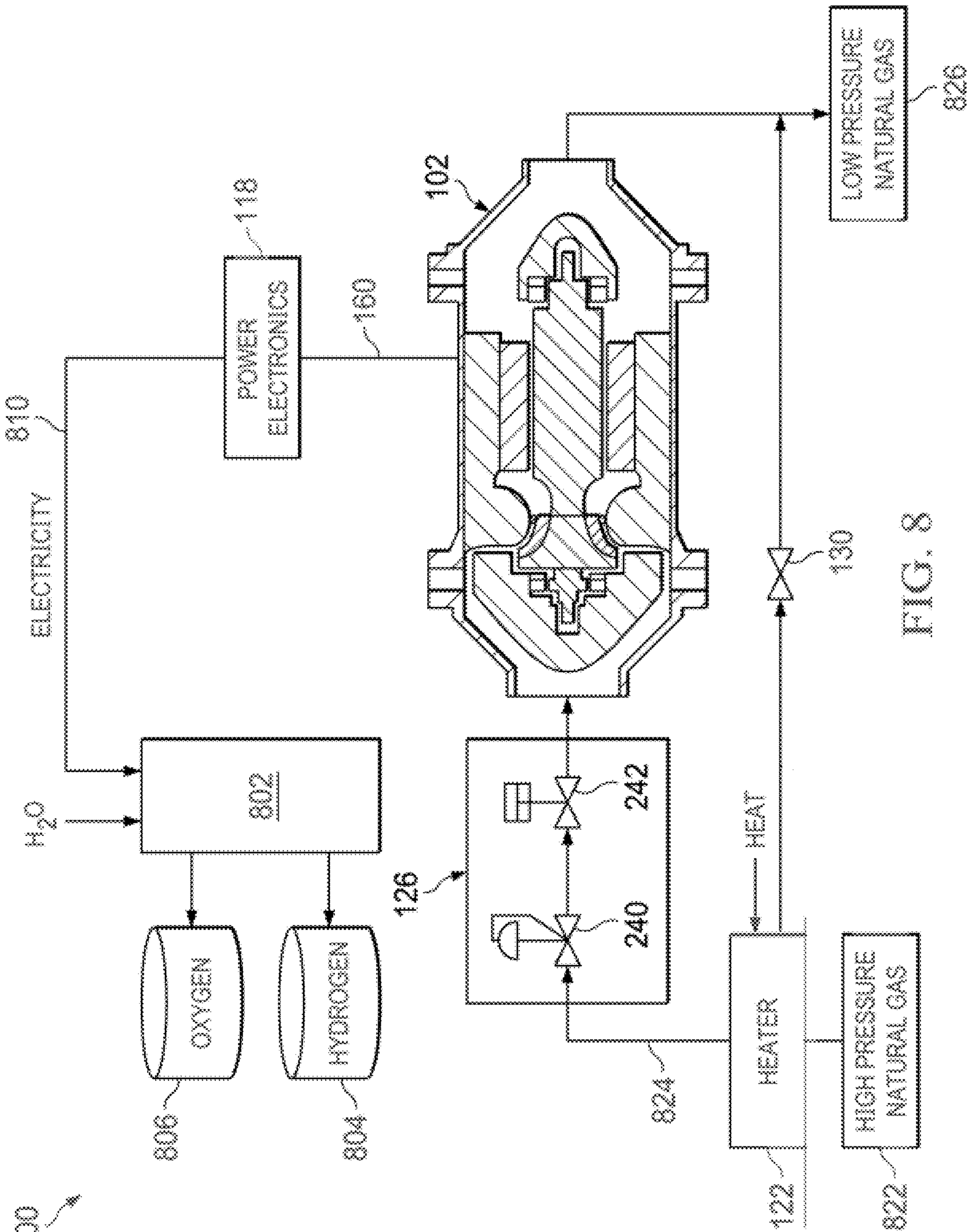
800
810
ELECTRICITY
POWER ELECTRONICS
118
160
102
LOW PRESSURE NATURAL GAS
826
H_2O
802
OXYGEN
HYDROGEN
806
804
126
242
240
130
HEATER
824
122
HIGH PRESSURE NATURAL GAS
822
HEAT

FIG. 8

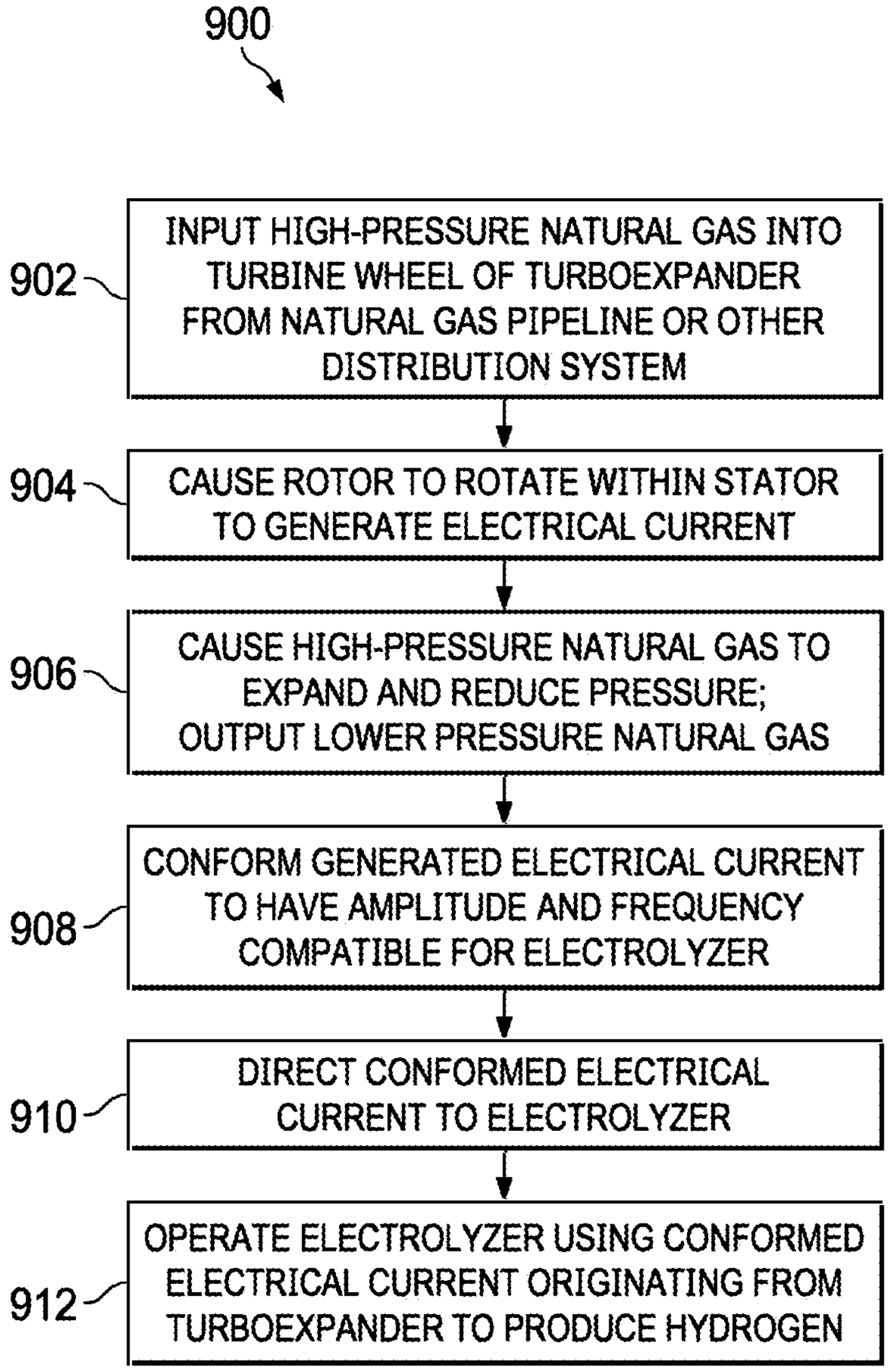
900
902
INPUT HIGH-PRESSURE NATURAL GAS INTO TURBINE WHEEL OF TURBOEXPANDER FROM NATURAL GAS PIPELINE OR OTHER DISTRIBUTION SYSTEM
904
CAUSE ROTOR TO ROTATE WITHIN STATOR TO GENERATE ELECTRICAL CURRENT
906
CAUSE HIGH-PRESSURE NATURAL GAS TO EXPAND AND REDUCE PRESSURE; OUTPUT LOWER PRESSURE NATURAL GAS
908
CONFORM GENERATED ELECTRICAL CURRENT TO HAVE AMPLITUDE AND FREQUENCY COMPATIBLE FOR ELECTROLYZER
910
DIRECT CONFORMED ELECTRICAL CURRENT TO ELECTROLYZER
912
OPERATE ELECTROLYZER USING CONFORMED ELECTRICAL CURRENT ORIGINATING FROM TURBOEXPANDER TO PRODUCE HYDROGEN

FIG. 9

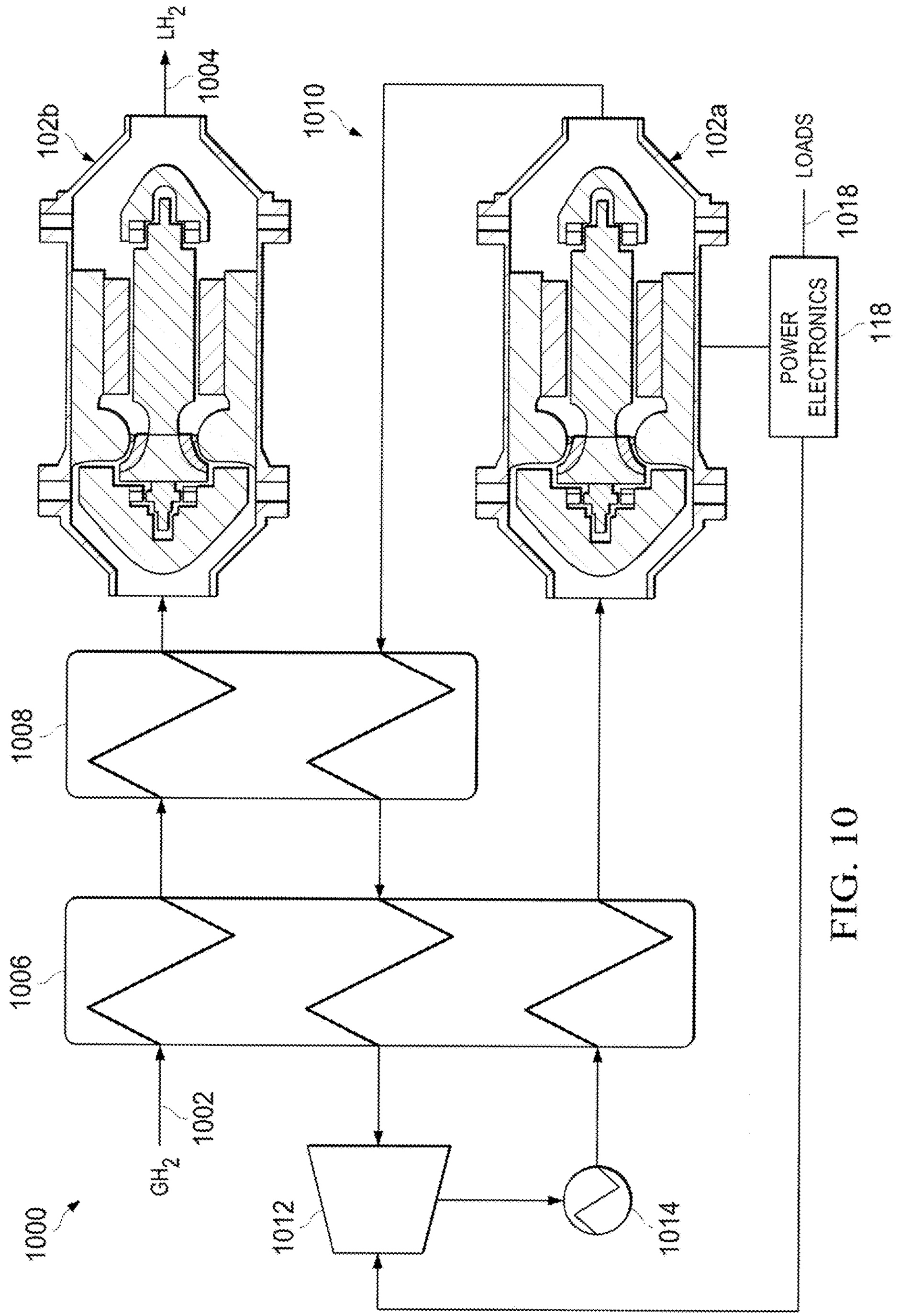
LH_2
1004
102b
1010
102a
LOADS
1018
POWER ELECTRONICS
118
1008
1006
GH_2
1002
1000
1012
1014

FIG. 10

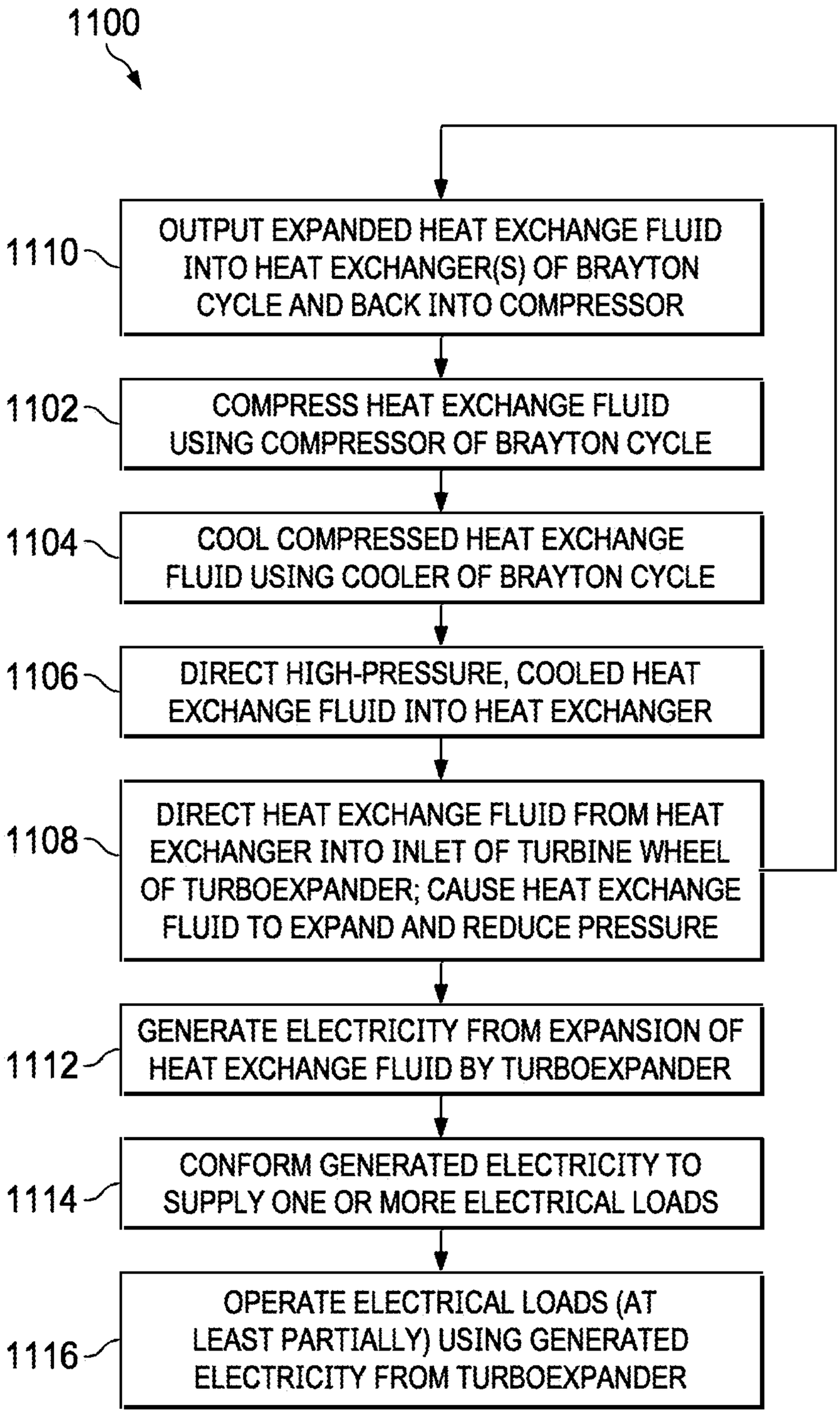
1100
1110
OUTPUT EXPANDED HEAT EXCHANGE FLUID INTO HEAT EXCHANGER(S) OF BRAYTON CYCLE AND BACK INTO COMPRESSOR
1102
COMPRESS HEAT EXCHANGE FLUID USING COMPRESSOR OF BRAYTON CYCLE
1104
COOL COMPRESSED HEAT EXCHANGE FLUID USING COOLER OF BRAYTON CYCLE
1106
DIRECT HIGH-PRESSURE, COOLED HEAT EXCHANGE FLUID INTO HEAT EXCHANGER
1108
DIRECT HEAT EXCHANGE FLUID FROM HEAT EXCHANGER INTO INLET OF TURBINE WHEEL OF TURBOEXPANDER; CAUSE HEAT EXCHANGE FLUID TO EXPAND AND REDUCE PRESSURE
1112
GENERATE ELECTRICITY FROM EXPANSION OF HEAT EXCHANGE FLUID BY TURBOEXPANDER
1114
CONFORM GENERATED ELECTRICITY TO SUPPLY ONE OR MORE ELECTRICAL LOADS
1116
OPERATE ELECTRICAL LOADS (AT LEAST PARTIALLY) USING GENERATED ELECTRICITY FROM TURBOEXPANDER

FIG. 11

HYDROGEN APPLICATIONS FOR TURBOEXPANDER MACHINES

BACKGROUND

The efficient and effective movement of gases from producing regions to consumption regions uses an extensive and elaborate transportation system. Gases transported via pipelines can be pressurized and can traverse long distances through pipelines at high pressures. For example, hydrogen is a rapidly expanding global energy storage market. Hydrogen is used in many manufacturing processes from petroleum refining to food processing. Hydrogen is also used as a fuel source for gas turbines and in a broad range of fuels cells to generate electricity in industrial and consumer transportation sectors. Other gases can also be transported through pipelines at high pressures, including propane, oxygen, carbon dioxide, and others.

SUMMARY

Aspects of the embodiments are directed to an apparatus that includes an electric generator that includes a fluid inlet configured to receive hydrogen at a first pressure, a turbine wheel configured to expand the hydrogen and rotate in response to expansion of the hydrogen flowing into an inlet of the turbine wheel and out of the outlet of the turbine wheel, a rotor coupled to the turbine wheel and configured to rotate with the turbine wheel, a stationary stator, the electric generator to generate an alternating current upon rotation of the rotor within the stator, and a fluid outlet configured to output hydrogen at a second pressure less than the first pressure. The apparatus also includes a power electronics system electrically connected to an electrical output of the electric generator and to receive alternating current from the electric generator.

In some embodiments, the fluid outlet is coupled to a fuel cell inlet of a fuel cell, and the fluid outlet configured to direct the hydrogen gas at the second pressure to the fuel cell.

In some embodiments, the power electronics is electrically coupled to the fuel cell, and wherein the power electronics is configured to condition the alternating current to have a frequency and amplitude compatible to power the fuel cell.

In some embodiments, fluid outlet is coupled to a gas turbine inlet of a gas turbine, and the fluid outlet configured to direct the hydrogen gas at the second pressure to the gas turbine.

In some embodiments, the fluid inlet is configured to receive hydrogen gas at the first pressure from a trailer container; and the fluid outlet is configured to output hydrogen gas at the second pressure to a compressor of a hydrogen gas storage facility.

In some embodiments, the power electronics is electrically coupled to the compressor, and wherein the power electronics is configured to condition the alternating current to have a frequency and amplitude compatible to power the compressor.

In some embodiments, the fluid inlet is configured to receive cooled heat exchange fluid at the first pressure from a first heat exchanger device hydrogen liquefaction system; and the fluid outlet is configured to output expanded heat exchange fluid at the second pressure to a second heat exchanger of the hydrogen liquefaction system.

In some embodiments, the power electronics is electrically coupled to one or more compressors of the first or second heat exchanger, and wherein the power electronics is configured to condition the alternating current to have a frequency and amplitude compatible to power the one or more compressors.

In some embodiments, the power electronics is electrically coupled to one or more compressors of a pre-cooling heat exchanger of the liquefaction system, and wherein the power electronics is configured to condition the alternating current to have a frequency and amplitude compatible to power the one or more compressors.

In some embodiments, the power electronics comprises a variable speed drive connected to the electrical output of the electric generator, the variable speed drive to convert the alternating current received from the electric generator into an alternating current compatible with a power grid.

In some embodiments, the variable speed drive includes a rectifier to receive alternating current from the electric generator and convert the alternating current into direct current; and an inverter to receive direct current from the rectifier and convert the direct current into an alternating current comprising an amplitude and frequency compatible with the power grid.

In some embodiments, the electric generator comprises a three-phase permanent magnet synchronous generator. In some embodiments, the electric generator comprises a three-phase electrical output, and wherein the brake resistor assembly comprises a brake resistor in series with each phase of the electrical output.

Aspects of the embodiments include a method that involves receiving hydrogen gas at a first pressure into a turbine wheel of an electric generator, the hydrogen gas being received at a first pressure into the turbine wheel causing the turbine wheel to rotate and causing the hydrogen gas to expand; causing a rotor to rotate within a stator of the electric generator by rotation of the turbine wheel; generating electrical current by the electric generator by rotation of the rotor within the stator; directing electrical current generated by the electric generator to a power electronics; and outputting hydrogen gas at a second pressure, the second pressure less than the first pressure.

Some embodiments include outputting the hydrogen gas at the second pressure to a fuel cell.

Some embodiments include conditioning, by the power electronics, the electrical current to be compatible with powering the fuel cell; and directing the conditioned electrical current to the fuel cell.

Some embodiments include receiving the hydrogen gas at the first pressure from a trailer container; and outputting the hydrogen gas at the second pressure to a compressor at a hydrogen gas storage facility.

Some embodiments include conditioning, by the power electronics, the electrical current to be compatible with powering the compressor.

Some embodiments include receiving cooled heat exchanger fluid at the first pressure from a first heat exchanger of a hydrogen liquefaction system; and outputting expanded heat exchanger fluid at the second pressure to a second heat exchanger the hydrogen liquefaction system.

Some embodiments include conditioning, using power electronics, the electrical current to have a frequency and amplitude compatible to power one or more compressors of the hydrogen liquefaction system.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram of an electric power generation system coupled to a power grid in accordance with embodiments of the present disclosure.

FIG. **2** is a schematic diagram of a hydrogen pressure letdown system that includes a turboexpander in accordance with embodiments of the present disclosure.

FIG. **3** is a process flow diagram for operating a turboexpander for high-pressure hydrogen gas pressure letdown in accordance with embodiments of the present disclosure.

FIG. **4** is a schematic diagram of a hydrogen fuel gas system that includes a turboexpander in accordance with embodiments of the present disclosure.

FIG. **5** is a process flow diagram for expanding hydrogen fuel gas using a turboexpander in accordance with embodiments of the present disclosure.

FIG. **6**A is a schematic diagram for a hydrogen storage container system that includes a turboexpander in accordance with embodiments of the present disclosure.

FIG. **6**B is a graphical representation of hydrogen pressure changes in a hydrogen trailer container and a hydrogen storage system in accordance with embodiments of the present disclosure.

FIG. **7** is a process flow diagram for transferring hydrogen from a trailer container to a storage tank using a turboexpander in accordance with embodiments of the present disclosure.

FIG. **8** is a schematic diagram of a hydrogen production system that includes a turboexpander in accordance with embodiments of the present disclosure.

FIG. **9** is a process flow diagram for producing hydrogen using a turboexpander in accordance with embodiments of the present disclosure.

FIG. **10** is a schematic diagram of a hydrogen liquefaction system that includes a turboexpander in accordance with embodiments of the present disclosure.

FIG. **11** is a process flow diagram for performing hydrogen liquefaction using a turboexpander in accordance with embodiments of the present disclosure.

Like reference symbols in the various drawings indicate like elements. Drawings not to scale.

DETAILED DESCRIPTION

The turboexpander described herein can be used for various hydrogen applications. The turboexpander can process high pressure hydrogen and convert the pressure energy into electricity for a variety of uses. Applications where the turboexpander can be implemented include: pipeline distribution pressure let down, hydrogen production, hydrogen fuel gas for gas turbines or combustion engines, hydrogen dispensing from trailers, and hydrogen liquefaction. Each of these applications provides a sufficient pressure drop and flow to operate and produce energy using the turboexpander described herein.

The power grid that the turboexpander can supply power to (and draw power from) can be a national or regional power grid, a local power grid for a city or district, or a small grid, local grid, or microgrid, such as an on-site grid that supplies power to a building, campus, industrial manufacturing or processing plant, or neighborhood.

FIG. **1** is a schematic diagram of an electric power generation system **100** coupled to a power grid **140** in accordance with embodiments of the present disclosure. The electric power generation system **100** can be added at a PLD station to capture energy from gas expansion from the PLD process, or in any of the other applications described above. The electric power generation system **100** includes a turboexpander **102** in parallel with a pressure control valve **130**. The turboexpander **102** is arranged axially so that the turboexpander **102** can be mounted in-line with a pipe. The turboexpander **102** acts as an electric generator by generating electrical energy from rotational kinetic energy derived from expansion of a gas through a turbine wheel **104**. For example, rotation of the turbine wheel **104** can be used to rotate a rotor **108** within a stator **110**, which then generates electrical energy.

FIG. **1** is a schematic diagram of an electric power generation system **100** coupled to a power grid **140** in accordance with embodiments of the present disclosure. The electric power generation system **100** can be added at a PLD station to capture energy from gas expansion from the PLD process. The electric power generation system **100** includes a turboexpander **102** in parallel with a pressure control valve **130**. The turboexpander **102** is arranged axially so that the turboexpander **102** can be mounted in-line with a pipe. The turboexpander **102** acts as an electric generator by generating electrical energy from rotational kinetic energy derived from expansion of a gas through a turbine wheel **104**. For example, rotation of the turbine wheel **104** can be used to rotate a rotor **108** within a stator **110**, which then generates electrical energy.

The turboexpander **102** is shown to have the process gas flow through the system, which cools the generator section and eliminates the need for auxiliary cooling equipment. In some embodiments, non-flow-through overhung systems can also be implemented. The power electronics **118** for turboexpander combines a Variable Speed Drive (VSD) **166** and Magnetic Bearing Controller (MBC) **168** into one cabinet, in some implementations. The VSD allows for a consistent and clean delivery of generated power from the turboexpander **102** to a power grid **140**. The VSD **166** regulates the frequency and amplitude of the generated current to match the local grid. After expansion, the gas exits the turboexpander **102** along the same axial path for downstream processes.

The turboexpander **102** is shown as having a flow-through configuration. The flow-through configuration permits process gas to flow from an inlet side of the turboexpander **102** to an outlet side of the turboexpander **102**. The gas flows into a radial gas inlet **154** to a turbine wheel **104** and an axial gas outlet **156** from the turbine wheel **104**. The gas then flow through the generator and out of the outlet **156**, where the gas rejoins the gas pipeline **170**. Generally, high pressure process gas **120** is directed to flow into the turboexpander **102** through a flow control system **126**. The flow control system **126** includes a flow or mass control valve and an emergency shut off valve. Flow control system **126** can be controlled electrically from power electronics **118** by control line **164**. In embodiments, the turboexpander housing **112** is hermetically sealed. As mentioned above, the turboexpander can be non-flow-through and overhung without deviating from the scope of this disclosure. The high pressure process gas **120** is expanded by flowing through the turbine wheel **104**, resulting in a pressure letdown of the process gas. Lower pressure process gas **128** exits the turboexpander. The expansion of the high pressure process gas **120** through the turbine wheel **104** causes the turbine wheel **104** to rotate, which causes the rotor **108** to rotate. The rotation of the rotor **108** within the stator **110** generates electrical energy. The turboexpander **102** achieves the desired pressure letdown and captures the energy from the pressure letdown to generate electricity. A pressure control valve **130**, such as a conventional pressure regulator, can be installed in parallel to the turboexpander **102**. The pressure control valve **130** can be used to control the pressure of the high pressure process gas **120** that flows through the turboexpander. Any excess high pressure process gas that is not directed into the

turboexpander can be directed through the pressure control valve **130**. In addition, upon deactivation of the turboexpander **102**, flow control system **126** can shut off process gas flow to the turboexpander. In that case, the pressure control valve **130** can be set to perform the pressure let-down for the high-pressure gas for downstream distribution and consumption.

The flow control system **126** can include a pressure relief valve, flow control valve, an emergency shut-off valve, etc. The flow control system **126** can use one or more valves to control the pressure of the hydrogen entering the turbine wheel **104** to achieve both a desired turbine wheel speed (and resulting electrical output) and a desired hydrogen output pressure from the turboexpander **102**.

In some embodiments, a heater **122** can heat the high pressure process gas **120** prior to flowing the gas into the turboexpander **102**. For example, if the expansion of the gas through the turbine wheel **104** lowers the temperature of the process gas to a point where moisture in the gas freezes at the turbine wheel or other downstream locations in the pipeline, the pressurized process gas **120** can be heated by heater **122**. (Heated) high pressure process gas **124** can then be directed into the turboexpander **102**. The heating of the process gas can prevent freezing moisture as the gas expands and its temperature drops.

The turboexpander **102** includes a turbine wheel **104**. The turbine wheel **104** is shown as a radial inflow turbine wheel, though other configurations are within the scope of this disclosure, such as axial flow turbine wheels. In this example, heated high pressure process gas **124** is received from an inlet conduit **150** of the housing **112** enters a radially oriented inlet **154** of the turbine wheel **104**. In certain embodiments, the fluid flows through an inlet conduit **150** and is diverted by a flow diverter to a radial inlet **154** that directs the flow into the radial inflow of the turbine wheel **104**. After expanding, the lower pressure process gas exits the turbine wheel **104** from an axially oriented outlet **156** to outlet conduit **152** of the housing **112**.

The turbine wheel **104** can be directly affixed to the rotor **108**, or to an intermediate common shaft, for example, by fasteners, rigid drive shaft, welding, or other manner. For example, the turbine wheel **104** may be received at an end of the rotor **108**, and held to the rotor **108** with a shaft. The shaft threads into the rotor **108** at one end, and at the other, captures the turbine wheel **104** between the end of rotor **108** and a nut threadingly received on the shaft. The turbine wheel **104** and rotor **108** can be coupled without a gearbox and rotate at the same speed. In other instances, the turbine wheel **104** can be indirectly coupled to the rotor **108**, for example, by a gear train, clutch mechanism, or other manner.

The turbine wheel **104** includes a plurality of turbine wheel blades **106** extending outwardly from a hub and that react with the expanding process gas to cause the turbine wheel **104** to rotate. FIG. **1** shows an unshrouded turbine wheel, in which each of the turbine blades **106** has an exposed, generally radially oriented blade tip extending between the radial inlet **154** and axial outlet **156**. As discussed in more detail below, the blade tips substantially seal against a shroud **114** on the interior of the housing **112**. In certain instances, the turbine wheel **104** is a shrouded turbine wheel.

In configurations with an un-shrouded turbine wheel **104**, the housing **112** includes an inwardly oriented shroud **114** that resides closely adjacent to, and at most times during operation, out of contact with the turbine wheel blades **106**. The close proximity of the turbine wheel blades **106** and shroud **114** substantially seals against passage of process gas there between, as the process gas flows through the turbine wheel **104**. Although some amount of the process gas may leak or pass between the turbine wheel blades **106** and the shroud **114**, the leakage is insubstantial in the operation of the turbine wheel **104**. In certain instances, the leakage can be commensurate with other similar unshrouded-turbine/shroud-surface interfaces, using conventional tolerances between the turbine wheel blades **106** and the shroud **114**. The amount of leakage that is considered acceptable leakage may be predetermined. The operational parameters of the turbine generator may be optimized to reduce the leakage. In embodiments, the housing **112** is hermetically sealed to prevent process gases from escaping the radial inlet **154** of the turbine wheel **104**.

The shroud **114** may reside at a specified distance away from the turbine wheel blades **106**, and is maintained at a distance away from the turbine wheel blades **106** during operation of the turboexpander **102** by using magnetic positioning devices, including active magnetic bearings and position sensors.

The turboexpander **102** can include a high-performance, high-speed permanent magnet generator. In certain embodiments, the turboexpander **102** includes a radial in-flow expansion turbine wheel **104**. Turboexpander **102** can also include low loss active magnetic bearings (AMBs) **116***a,b*. The rotor assembly can include permanent magnet section with the turbine wheel **104** mounted directly to the rotor hub. The rotor **108** can be levitated by the magnetic bearing system creating a frictionless (or near frictionless) interface between dynamic and static components. The AMBs **116***a,b* facilitate a lossless (or near lossless) rotation of the rotor **108**.

Bearings **116***a* and **116***b* are arranged to rotatably support the rotor **108** and turbine wheel **104** relative to the stator **110** and the shroud **114**. The turbine wheel **104** is supported in a non-cantilevered manner by the bearings **116***a* and **116***b*. In embodiments, the turbine wheel **104** may be supported in a cantilevered manner and bearings **116***a* and **116***b* may be located on the outlet side of turbine wheel **104**. In certain instances, one or more of the bearings **116***a* or **116***b* can include ball bearings, needle bearings, magnetic bearings, foil bearings, journal bearings, or others.

Bearings **116***a* and **116***b* may be a combination radial and thrust bearing, supporting the rotor **108** in radial and axial directions. Other configurations could be utilized. The bearings **116***a* and **116***b* need not be the same types of bearings.

In the embodiments in which the bearings **116***a* and **116***b* are magnetic bearings, a magnetic bearing controller (MBC) **168** is used to control the magnetic bearings **116***a* and **116***b*. Position sensors **117***a*, **117***b* can be used to detect the position or changes in the position of the turbine wheel **104** and/or rotor **108** relative to the housing **112** or other reference point (such as a predetermined value). Position sensors **117***a*, **117***b* can detect axial and/or radial displacement. The magnetic bearing **116***a* and/or **116***b* can respond to the information from the position sensors **117***a*, **117***b* and adjust for the detected displacement, if necessary. The MBC **168** may receive information from the position sensor(s) **117***a*, **117***b* and process that information to provide control signals to the magnetic bearings **116***a*, **116***b*. MBC **168** can communicate with the various components of the turboexpander **102** across a communications channel **162**.

The use of magnetic bearings **116***a*, **116***b* and position sensors **117***a*, **117***b* to maintain and/or adjust the position of the turbine wheel blades **106** such that the turbine wheel blades **106** stay in close proximity to the shroud **114** permits

the turboexpander **102** to operate at high efficiencies. The use of the active magnetic bearings **116***a,b* in the turboexpander **102** eliminates physical contact between rotating and stationary components, as well as eliminate lubrication and lubrication systems. In some embodiments, brush seals can be used to prevent gas leakage. The magnetic bearings **116***a,b* and position sensors **117***a,b* allow for the rotor to stay in close proximity to the brush seals **157**.

The turboexpander **102** may include one or more backup bearings. For example, at start-up and shut-down or in the event of a power outage that affects the operation of the magnetic bearings **116***a* and **116***b*, bearings may be used to rotatably support the rotor **108** during that period of time. The backup bearings and may include ball bearings, needle bearings, journal bearings, or the like. As mentioned previously, the turboexpander **102** is configured to generate electricity in response to the rotation of the rotor **108**. In certain instances, the rotor **108** can include one or more permanent magnets. The stator **110** includes a plurality of conductive coils. Electrical current is generated by the rotation of the magnet within the coils of the stator **110**. The rotor **108** and stator **110** can be configured as a synchronous, permanent magnet, multiphase alternating current (AC) generator. The bi-directional electrical connection **160** can include a three-phase output, for example. The bi-directional electrical connection **160** can facilitate conveyance of (e.g., 3 phase) power output from the generator and can also supply power to the generator for start-up (e.g., to cause the rotor to begin rotating while process gas or other working fluid pressure builds up and can spin the rotor **108** and turbine wheel **104**). In certain instances, stator **110** may include a plurality of coils (e.g., three or six coils for a three-phase AC output). When the rotor **108** is rotated, a voltage is induced in the stator coil. At any instant, the magnitude of the voltage induced in coils is proportional to the rate at which the magnetic field encircled by the coil is changing with time (i.e., the rate at which the magnetic field is passing the two sides of the coil). In instances where the rotor **108** is coupled to rotate at the same speed as the turbine wheel **104**, the turboexpander **102** is configured to generate electricity at that speed. Such a turboexpander **102** is what is referred to as a "high speed" turbine generator. For example, in embodiments, the turboexpander **102** can produce up to 280 kW at a continuous speed of 30,000 rpm. In embodiments, the turboexpander can produce on the order of 350 kW at higher rotational speeds (e.g., on the order of 35,000 rpm).

In some embodiments, the design of the turbine wheel **104**, rotor **108**, and/or stator **110** can be based on a desired parameter of the output gas from the turboexpander **102**. In some embodiments, the design of the turbine nozzle **155** can also be based on a desired parameter of the output gas from the turboexpander **102**. For example, the design of the turbine nozzle and turbine wheel can be based on a desired temperature of the gas **128**.

The turboexpander **102** can be coupled to a power electronics **118**. Power electronics **118** can include a variable speed drive (VSD) **166** (or variable frequency drive) and the magnetic bearing controller (MBC) **168** (discussed above).

The bi-directional electrical connection **160** of the turboexpander **102** is connected to the VSD **166**, which can be programmed to specific power requirements. The VSD **166** can include an insulated-gate bipolar transistor (IGBT) rectifier **208** to convert the variable frequency, high voltage output from the turboexpander **102** to a direct current (DC). The rectifier **208** can be a three-phase rectifier for three-phase AC input current. An inverter **210** then converts the DC from the rectifier AC for supplying to the power grid **140**. The inverter **210** can convert the DC to 380 VAC-480 VAC at 50 to 60 Hz for delivery to the power grid **140**. The specific output of the VSD **166** depends on the power grid and application. Other conversion values are within the scope of this disclosure. The VSD **166** matches its output to the power grid **140** by sampling the grid voltage and frequency, and then changing the output voltage and frequency of the inverter to match the sampled power grid voltage and frequency. In embodiments, rectifier **208** and inverter **210** are bi-directional, so that power from the grid **140** can be supplied to the turboexpander **102**. Power from the grid **140** can be used to start rotation of the rotor **108** within the stator **110** during start-up.

The turboexpander **102** is also connected to the MBC **168** in the power electronics **118**. The MBC **168** constantly monitors position, current, temperature, and other parameters to ensure that the turboexpander **102** and the active magnetic bearings **116***a* and **116***b* are operating as desired. For example, the MBC **168** is coupled to position sensors **117***a*, **117***b* to monitor radial and axial position of the turbine wheel **104** and the rotor **108**. The MBC **168** can control the magnetic bearings **116***a*, **116***b* to selectively change the stiffness and damping characteristics of the magnetic bearings **116***a*, **116***b* as a function of spin speed. The MBC **168** can also control synchronous cancellation, including automatic balancing control, adaptive vibration control, adaptive vibration rejection, and unbalance force rejection control.

Pressure let down systems convert kinetic energy from the process flow into shaft power. The turboexpander can support islanding operations. The turboexpander can continue to provide power to a location in the event that a power grid supplying power to that location is interrupted. This disclosure describes components that can facilitate load matching between the shaft power converted from the process gas flow at the pressure letdown station to load demands. In this way, the turboexpander can support microgrid functionality for islanding operations.

The turboexpander **102** described above includes example features that are implementation-specific. Certain features may be changed, added, removed, or redesigned without deviating from the scope of this disclosure. For example, other types of bearings can be used instead of or in addition to AMBs, such as ball bearings, fluid film bearings, etc. Different designs of rotors and stators can be used, such as brushless DC, induction-type, etc. Other types of stator cooling architectures can be used, such as non-flow-through and overhung architectures.

Distribution pipelines contain the highest gas flow rates in the distribution network and therefore offer the highest power potential for turboexpander-based pressure reduction. Both natural gas and hydrogen pressure reduction stations can utilize multiple turboexpander units in parallel to maximize power production (though one turboexpander is shown in the figures). Potential power generation in high-flow applications can yield up to 3 megawatts (MW) of power potential, the equivalent of about 12,000 tons of CO2e emissions offset annually.

Hydrogen is compressed for traversal through a pipeline and the pressure of the hydrogen will be reduced along the pipeline, as hydrogen flows from high pressure to low pressure. During distribution pressure drops (e.g., using pressure letdown (PLD) or pressure reduction stations (PRS)), usable energy can be recovered by the turboexpander **102** to generate clean electricity. Such a topology is illustrated generally by FIG. **1** described above and more specifically by FIG. **2**.

FIG. **2** is a schematic diagram of a hydrogen pressure letdown system **200** that includes a turboexpander **102** in accordance with embodiments of the present disclosure. The hydrogen pressure letdown system **200** includes a turboexpander **102** or similar turboexpander. The turboexpander **102** receives high-pressure hydrogen gas **222** from a pipeline, for example, as part of a hydrogen gas pressure letdown process. The high-pressure hydrogen gas can enter a turbine wheel of the turboexpander. The high-pressure hydrogen gas can cause the turbine wheel to rotate, thereby rotating a rotor within a stator. Rotation of the rotor within the stator can generate electrical current. The electrical current can be output from the turboexpander to a power electronics **118**. Power electronics **118** can convert the electrical current to be compatible with the grid **140** or other electrical loads. This electricity can be consumed on-site by the facility, consumed on-site in some energy intensive process such as green hydrogen production, or sold to the local energy utility creating a revenue stream for the pipeline owner.

High-pressure hydrogen gas **222** can traverse a pipeline and enter the hydrogen pressure letdown system **200**. The hydrogen pressure letdown system **200** includes a flow control system (e.g., flow control system **126** of FIG. **1**) and a pressure control valve **130** (also shown in FIG. **1**). The flow control system **126** can include a flow control valve (FCV) **240** and an emergency shutoff valve (ESV) **242**. FCV **240** can control the pressure of the flow of the high-pressure hydrogen gas **222** that enters the turboexpander **102**. The flow rate of the high-pressure hydrogen gas **222** can be controlled by the FCV **240** based on the size of the turbine wheel **104** and the desired power output of power electronics **118**; the rotational speed of the rotor **108** can be determined based on the desired rotordynamic performance of the rotor **108**. The FCV **240** can be controlled manually or electronically. The FCV **240**, for example, can be controlled electronically based on information about the power output in power electronics **118**. If the power output is too low, FCV **240** can be adjusted to increase flow rate of high-pressure hydrogen gas **222** input to the turboexpander **102** to increase the torque of rotor **108**; conversely, if power output is too high, FCV **240** can be adjusted to decrease flow rate of high-pressure hydrogen gas **222** input to the turboexpander **102** to decrease the torque of rotor **108**.

The flow control system **126** can also include ESV **242**. ESV **242** can close quickly to prevent high-pressure hydrogen gas **222** from entering the turboexpander **102** during emergency situations. Emergency situations can include rotor over-speed conditions, hydrogen gas leaks, fault conditions at the power electronics **118** or grid **140** or elsewhere (which can cause rotor over-speed), or other emergency situations.

The turboexpander **102** can expand the high-pressure hydrogen gas **222**, resulting in low (or lower) pressure hydrogen gas **224**. The low-pressure hydrogen gas **224** can be directed to downstream pipelines or elsewhere for distribution. The expansion of the high-pressure hydrogen gas **222** by the turbine wheel **104** of the turboexpander **102** results in the generation of electrical current. The electrical current can be output by the turboexpander **102** through bi-directional electrical connection **160** to power electronics **118**. Power electronics **118** can convert the generated electrical current into a form compatible with intended consumers of the electrical current. For example, power electronics **118** can change the amplitude and frequency of the generated electrical current to be compatible with supplying power to grid **140** or to electrical loads.

The power electronics **118** can include a variable speed drive (VSD) **206**. VSD **206** can include circuitry that can change electrical current to suit a specific load or the grid. For example, the VSD **206** can include circuitry that can convert the generated electrical current from AC to DC (e.g., a rectifier circuit) and from DC to AC (e.g., inverter circuit). The VSD **206** can include a bi-directional inverter **212** to allow the turboexpander to receive power from the grid for start-up. The VSD **206** can also include circuitry to change the waveform of the generated electrical current to conform the electrical current to have a frequency and amplitude compatible with the power grid **140**. Other electrical circuits are also contemplated and are within the scope of this disclosure.

The power electronics **118** can include a brake resistor assembly **202**. The brake resistor assembly **202** can be used to oppose run-away current generation during rotor over-speed conditions to slow the rotor rotation speed to prevent damage to the rotor. The brake resistor assembly **202** can be coupled to the bi-directional electrical connection **160** by a contactor **204**. Contactor **204** can close the circuit between the turboexpander power output and the brake resistor quickly to protect the rotor based on the detection **220** of an over-speed condition. The brake resistor assembly **202** impedance can be selected (or tuned) based on the power output of the turboexpander. The brake resistor assembly **202** can include a plurality of resistors (and in some cases resistors and capacitors). Though shown as part of the power electronics **118**, it is understood that the brake resistor assembly **202** and contactor **204** can be directly connected to the output of the turboexpander **102**, to reduce the latency between detecting the fault condition responsible for rotor over-speed and the closing of the contactor **204**.

FIG. **3** is a process flow diagram **300** for operating a turboexpander for high-pressure hydrogen gas pressure letdown in accordance with embodiments of the present disclosure. High-pressure hydrogen gas is input into turbine wheel of turboexpander (**302**). The high-pressure hydrogen gas input into the turbine wheel can cause the turbine wheel to rotate, which causes a rotor to rotate within a stator (**304**). The turbine wheel also expands the high-pressure hydrogen gas, thereby lowering the pressure of the hydrogen gas. This low (or lower)-pressure hydrogen gas is output from the turboexpander for downstream distribution and consumption (**306**).

The electrical current generated by the turboexpander can be output to a power electronics system. The power electronics can adjust the electrical current to be a form compatible with the intended load(s) or for supplying to the grid (**308**). The power electronics system can output the adjusted electrical current to the intended load(s) or to the grid (**310**).

It is understood that the order of operations shown in FIG. **3** (or in other process flow figures described herein) can be performed in a different order. Some processes are performed in parallel. For example, the turboexpander will generate electrical current once the turboexpander rotor is rotating at a certain speed with a certain torque. The flow of the hydrogen gas can be continuous, which maintains the desired power output from the power electronics. While the rotor is spinning at the desired speed, the expanded hydrogen gas is output from the turboexpander and directed downstream and the electrical current is output from the power electronics. These processes of generating electrical current by the turboexpander from expansion of high-pressure hydrogen gas can continue until the system is shut down for whatever reason.

The pressure letdown application shown in FIG. **2** can be used in combination with other hydrogen applications. Generally, the turboexpander **102** can be used to expand high-pressure hydrogen gas **222** and output lower pressure hydrogen gas **224** and generate electrical current.

FIG. **4** is a schematic diagram of a hydrogen-based power station **400** that includes a turboexpander **102** in accordance with embodiments of the present disclosure. Hydrogen is used to generate power in gas turbines (such as gas turbine **410**) and fuel cells (such as fuel cell **412**). Both applications use large volumes of hydrogen, which can be supplied by on-site storage or by a co-located production facility via pipeline. The pipeline or storage pressure is reduced (or let down) before the hydrogen enters the gas turbine **410** or fuel cell **412**. The turboexpander **102** can be used to recover energy from pressure reduction of the hydrogen fuel gas.

In some circumstances, the volumetric flow rate in these applications can be on the order of 1,000 to 5,000 Nm3/h. The potential recoverable power ranges from 10 kW up to 300 kW, which can be enough to improve overall plant efficiency. One example use for the generated power is to offset the electrical demand of the facility. The economic benefit or return on investment can then be evaluated using the retail price of electricity rather than the wholesale price for selling the electricity to the grid.

At the outset, high-pressure hydrogen gas **404** is delivered to the hydrogen-based power station **400** from a hydrogen fuel gas source **402**. The hydrogen fuel gas source can include a hydrogen storage tank or a hydrogen pipeline. The hydrogen-based power station **400** includes a flow control system **126** and a pressure control valve **130**. As mentioned before, flow control system **126** includes a FCV **240** and ESV **242**. Flow control system **126** can control the flow of high-pressure hydrogen fuel gas **404** into the turbine wheel **104** of the turboexpander **102**. The turbine wheel **104** of the turboexpander **102** can expand and reduce the pressure of the high-pressure hydrogen fuel gas **404**. The low (or lower)-pressure hydrogen fuel gas **406** can be supplied to a hydrogen-based power system **408**, such as a gas turbine **410** or fuel cell **412**. The hydrogen-based power system **408** can provide power to the grid or to one or more loads.

The energy reclaimed from the pressure letdown of the high-pressure hydrogen fuel gas **404** by the turbine wheel **104** is used to generate electrical current. The expansion of the high-pressure hydrogen fuel gas **404** causes the turbine wheel **104** to rotate, thereby rotating a rotor **108**. Rotation of the rotor **108** within the stator **110** generates electrical current. The electrical current can be used to power certain loads, such as those at the power station facility; or the electrical current can be used to supply power to the grid. For example, electrical current generated by the turboexpander **102** can be directed to a power electronics **118** (described above). Power electronics **118** can include circuitry to condition the generated electrical current to be compatible with the load(s) or the grid. The power electronics **118** can also condition the power generated by the turboexpander **102** to have a frequency and amplitude compatible with the gas turbine **410** or the fuel cell **412**.

FIG. **5** is a process flow diagram for expanding hydrogen fuel gas using a turboexpander in accordance with embodiments of the present disclosure. High-pressure hydrogen fuel gas is input into turbine wheel of turboexpander (**502**). The high-pressure hydrogen fuel gas input into the turbine wheel can cause the turbine wheel to rotate, which causes a rotor to rotate within a stator (**504**). The turbine wheel also expands the high-pressure hydrogen fuel gas, thereby lowering the pressure of the hydrogen fuel gas. This low (or lower)-pressure hydrogen fuel gas is output from the turboexpander for downstream distribution and consumption (**506**).

The electrical current generated by the turboexpander can be output to a power electronics. The power electronics can condition the electrical current to be compatible with the intended load(s) or for supplying to the grid (**508**). The power electronics can output the adjusted electrical current to the intended load(s) or to the grid (**510**).

FIG. **6**A is a schematic diagram for a hydrogen fueling station **600** that includes a turboexpander in accordance with embodiments of the present disclosure. Hydrogen gas can be transported from a starting point to hydrogen fueling station **600** via bulk delivery trailers. Hydrogen gas is offloaded from the hydrogen gas trailer container **602** to onsite storage **614** at the fueling station **600**, where the hydrogen gas is stored until it is dispensed to consumers' vehicles. The use of trailers for transporting hydrogen gas is useful while a global hydrogen pipeline infrastructure is being constructed and implemented.

These bulk trailers deliver gaseous hydrogen **604** at high pressure (~700-bar) which is bled into a storage container **614** at the hydrogen fueling station **600**. This process includes expansion of high-pressure hydrogen gas **604**. In embodiments of this disclosure, turboexpander **102** can be used to control the expansion of the high-pressure hydrogen gas **604** from the trailer container **602** and reclaim energy from the expansion of the high-pressure hydrogen gas to generate electrical current. During the initial portion of the trailer offloading process, when the pressure of the H2 gas trailer **602** is at a pressure higher than that of the H2 Gas storage **614**, the turboexpander **102** can be used to recover expansion energy by generating electrical current. This electrical current can be used to offset at least some of the electrical demand required to run compressor **612**, which is used to pump hydrogen gas into the hydrogen gas storage container **614** at a latter portion of the emptying process when the pressure of the H2 gas trailer **602** is at a pressure lower than that of the H2 Gas storage **614**.

At the outset, high-pressure hydrogen gas **604** is delivered to the hydrogen fuel station **600** by a hydrogen gas trailer **602**. The hydrogen fuel station **400** includes a flow control system **126** and a pressure control valve **130**. As mentioned before, flow control system **126** includes a FCV **240** and ESV **242**. Flow control system **126** can control the flow of high-pressure hydrogen gas **604** into the turbine wheel **104** of the turboexpander **102**. The turbine wheel **104** of the turboexpander **102** can expand and reduce the pressure of the high-pressure hydrogen gas **604**.

The energy reclaimed from the pressure letdown of the high-pressure hydrogen gas **604** by the turbine wheel **104** is used to generate electrical current. The expansion of the high-pressure hydrogen gas **604** causes the turbine wheel **104** to rotate, thereby rotating a rotor **108**. Rotation of the rotor **108** within the stator **110** generates electrical current. The electrical current can be used to power certain loads, such as compressor **612** via a battery storage system **614**, or at least offset the power consumed by compressor **612** by selling generated power to the grid or by using the generated power to power other loads at the facility. For example, electrical current generated by the turboexpander **102** can be directed to a power electronics **118** (described above). Power electronics **118** can include circuitry to condition the generated electrical current to be compatible with the battery storage system **614**, or other load(s) at the fueling station or the grid.

FIG. **6**B is a graphical representation **620** of hydrogen pressure changes in a hydrogen trailer container and a hydrogen storage system in accordance with embodiments of the present disclosure. As the hydrogen pressure in the trailer container falls, a compressor is used to pump the hydrogen into the storage tank. The compressor can be powered by the turboexpander via a battery storage system, as shown in FIG. **6**A to fill the storage tank at the fueling station with pressurized hydrogen.

FIG. **7** is a process flow diagram for transferring hydrogen from a trailer container to a storage tank using a turboexpander in accordance with embodiments of the present disclosure. High-pressure hydrogen gas is input into turbine wheel of turboexpander from the trailer container (**702**). The high-pressure hydrogen gas input into the turbine wheel can cause the turbine wheel to rotate, which causes a rotor to rotate within a stator (**704**). The turbine wheel also expands the high-pressure hydrogen gas, thereby lowering the pressure of the hydrogen gas. This low (or lower)-pressure hydrogen gas is output from the turboexpander into a storage container at the fueling station (**706**).

The electrical current generated by the turboexpander can be output to a power electronics. The power electronics can condition the electrical current to be compatible with a battery storage system, as well as other facility load(s) or for supplying to the grid (**708**). The power electronics can output the adjusted electrical current to battery storage system or intended load(s) or to the grid (**710**). The compressor can be operated using the power generated from the expansion of the hydrogen gas to pump the hydrogen gas into the fuel tank (**712**).

FIG. **8** is a schematic diagram of a hydrogen production system **800** that includes a turboexpander **102** in accordance with embodiments of the present disclosure. The turboexpander **102** can recover energy lost during pressure let down in a natural gas distribution network. Natural gas distribution is an energy intensive process that uses several megawatt class compressors to pressurize the gas and transmit it along thousands of miles of pipeline. At city gate Pressure Reduction Stations (PRS), this compressed pipeline gas is reduced to a pressure suitable for distribution to local businesses, energy production, and residential use.

At PRS, instead of pressure reduction valves or Joule-Thomson (JT) valves, the turboexpander **102** can be used to reduce the pressure. The energy from the expansion of the natural gas can be recovered and converted into useable electricity using the turboexpander **102**.

Some PRS are located in remote areas with limited access to the surrounding electrical grid. Therefore, locally consuming the generated power is desirable. In embodiments, the power generated by the turboexpander **102** can be consumed for green hydrogen production through electrolysis. The electricity generated from the turboexpander **102** can power a bank of electrolyzers, which can produce hydrogen and oxygen from water.

Current polymer electrolyte membrane (PEM) electrolyzer efficiencies range from 70 to 82% with the expectation of reaching 86% by **2030** according to the Fuel Cells and Hydrogen Joint Undertaking. Current PEM technology produces about 1 kg of hydrogen per 50 kWh of electricity, thus a 280 kW FIT system producing 2.45 GWh of power per year can produce up to 54 tons of green hydrogen annually. Production of green hydrogen from clean and renewable energy sources will play an integral role in meeting The Paris Agreement goals.

In FIG. **8**, the hydrogen production system **800** is linked to a natural gas PRS that links a pipeline that can transport high-pressure natural gas **822**. The high-pressure natural gas **822** can be heated using heater **122**. The heated, high-pressure natural gas can be directed into the turboexpander **102** through a flow control system **126**. The hydrogen production system **800** includes a flow control system **126** and a pressure control valve **130**. As mentioned before, flow control system **126** includes a FCV **240** and ESV **242**. Flow control system **126** can control the flow of heated, high-pressure natural gas **824** into the turbine wheel **104** of the turboexpander **102**. The turbine wheel **104** of the turboexpander **102** can expand and reduce the pressure of the heated, high-pressure natural gas **824**. The low (or lower)-pressure natural gas **826** is directed to the pipeline for downstream distribution and consumption.

The energy reclaimed from the pressure letdown of the heated, high-pressure natural gas **824** by the turbine wheel **104** is used to generate electrical current. The expansion of the heated, high-pressure natural gas **824** causes the turbine wheel **104** to rotate, thereby rotating a rotor **108**. Rotation of the rotor **108** within the stator **110** generates electrical current. The electrical current can be used to power electrolyzer **802**, or at least offset the power consumed by electrolyzer **802** by selling generated power to the grid or by using the generated power to power other loads at the hydrogen production station **800**. For example, electrical current generated by the turboexpander **102** can be directed to a power electronics **118** (described above). Power electronics **118** can include circuitry to condition the generated electrical current from the turboexpander to be compatible with the electrolyzer **802**, or other load(s) at the hydrogen production system **800** or the grid.

The electrolyzer **802** can use water as an input to produce hydrogen **804** and oxygen **806** through electrolysis. The hydrogen can then be transported offsite by trailer or blended into the natural gas pipeline.

FIG. **9** is a process flow diagram for producing hydrogen using a turboexpander in accordance with embodiments of the present disclosure. High-pressure natural gas is input into turbine wheel of turboexpander from (**902**). The high-pressure natural gas input into the turbine wheel can cause the turbine wheel to rotate, which causes a rotor to rotate within a stator (**904**). The turbine wheel also expands the high-pressure natural gas, thereby lowering the pressure of the natural gas. This low (or lower)-pressure natural gas is output from the turboexpander for downstream distribution and consumption (**906**).

The electrical current generated by the turboexpander can be output to a power electronics. The power electronics can condition the electrical current to be compatible with an electrolyzer for a hydrogen production process system (**908**). The power electronics can output the adjusted electrical current to power the electrolyzer (**910**). The electrolyzer can then operate to produce hydrogen, as described in the text accompanying FIG. **8** (**912**).

FIG. **10** is a schematic diagram of a hydrogen liquefaction system **1000** that includes a turboexpander in accordance with embodiments of the present disclosure. Hydrogen, like other gases, is most efficiently transported in its liquid state. The liquefaction process shown in FIG. **10** can be used to convert hydrogen gas (GH_2 **1002**) into liquid hydrogen (LH_2 **1004**). A series of processes are used to reduce the temperature of the GH_2 **1002** down to −253° C., including compression, heat exchange, and expansion. The turboexpander **102** can be used to recover energy lost during the expansion of H2 and the expansion of the closed-loop heat exchange fluid (such as hydrogen, helium, or nitrogen).

The example liquefaction system **1000** shown in FIG. **10**, two heat exchangers (e.g., heat exchanger **1006** and heat exchanger **1008**) are used. The heat exchangers drop the temperature from the incoming GH2 **1002** and the exiting LH2 **1004**. There may be more than two heat exchangers (or more than two heat exchange processes). Other equipment may also be included in this portion of the system that are not illustrated, such as compressors or other devices. Heat exchanger can include pre-cooling heat exchanger, cryogenic heat exchangers, etc.

The heat exchange system **100** also includes a closed-loop Brayton cycle **1010**. The closed-loop Brayton cycle includes a compressor **1006** for compressing the heat exchange fluid. The compressor **1012** directs the heat exchange fluid into a cooler **1014**. The cooled heat exchange fluid can be used in heat exchanger **1006** to cool hydrogen The turboexpander **102***a* can be used to further expand and cool the heat exchange fluid for use in heat exchanger **1008** and in heat exchanger **1006** to further cool the hydrogen. The heat exchange fluid is then directed into the compressor **1012** to continue the Brayton cycle **1010**.

The expansion of the heat exchange fluid by the turbine wheel of the turboexpander **102***a* can result in the generation of electricity. The power generated by the turboexpander **102***a* by the expansion of the heat exchange fluid can be used to power loads. Power electronics **118** can condition the electricity output by the turboexpander for use by one or more loads. For example, electricity generated by the turboexpander **102***a* can be used to power the compressor **1012** (or offset power used by the compressor **1012**). The turboexpander **102***a* can also provide power to other loads **1018**. Such loads can include other devices that are part of the liquefaction process, such as compressors in the heat exchangers **1006**, **1008** or other devices.

In some embodiments, a turboexpander **102***b* can also be used to generate electricity from the expansion of the hydrogen in the liquefaction process. Power generated from hydrogen expansion can be used to power compressors or other devices.

FIG. **11** is a process flow diagram for performing hydrogen liquefaction using a turboexpander in accordance with embodiments of the present disclosure. As mentioned above, the liquefaction system includes heat exchangers and a closed-loop Brayton cycle. The Brayton cycle can include a compressor that compresses heat exchange fluid (**1102**). The compressed heat exchange fluid can be cooled by a cooling device (**1104**). The pressurized and cooled heat exchange fluid can be used in a heat exchanger of the hydrogen liquefaction process (**1106**). The heat exchange fluid can be expanded by a turbine wheel of a turboexpander (**1108**). The expansion of the heat exchange fluid by the turbine wheel of the turboexpander reduces the pressure of the heat exchange fluid and causes a rotor coupled to the turbine wheel to rotate.

The expanded heat exchange fluid can be output from the turboexpander and directed back into the Brayton cycle, and into heat exchangers of the liquefaction process to cool hydrogen (**1110**). The heat exchange fluid can then be directed back into the compressor (**1102**).

The rotation of the rotor of the turboexpander can result in the generation of electricity (**1112**). The electricity can be conditioned by power electronics so that it is compatible to supply power to one or more loads (**1114**), including one or more compressors of the Brayton cycle and/or the heat exchangers. The compressor(s) can be operated (at least partially) by the power generated by the turboexpander (**1116**).

In some embodiments, energy lost during expansion of the hydrogen during the liquefaction process can also be used to rotate a turbine wheel of a turboexpander to generate electricity. Likewise, such power can be used to operate various loads, including compressors of the heat exchangers or other devices.

The use of turboexpander **102** for generating electricity from gas expansion offers the following benefits in the liquefaction process:

1. Magnetic bearings allow for oil and air free operation eliminating process gas contamination
2. Magnetic bearings offer a long life (25 years), maintenance-free operation
3. System is designed to deliver 125 kW or 280 kW, a convenient and scalable power building block for liquefactions plants
4. Modular design allows for low capital costs instead of a custom-engineered solution
5. Flow-through design eliminates dynamic seals and risks of leaks
6. Energy balance due to generator loaded design

Existing liquefaction plants process up to 40 tons per day (tpd) of liquid hydrogen, creating ~400 kW of potential power generation from the turboexpander **102**. Future liquefaction plants are being designed with capacities up to 200 tpd, creating ~2 MW of clean power. Based on 2019 U.S. totals from the Energy Information Administration, 2 MW of power generation equates to 8,000 tons per year of CO2 equivalent (CO2e) emissions offset.

The specification and drawings are, accordingly, to be regarded in an illustrative sense rather than a restrictive sense. Furthermore, the foregoing use of embodiment and other exemplarily language does not necessarily refer to the same embodiment or the same example, but may refer to different and distinct embodiments, as well as potentially the same embodiment. In the foregoing specification, a detailed description has been given with reference to specific exemplary embodiments. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader spirit and scope of the disclosure as set forth in the claims.

What is claimed is:

1. An apparatus comprising:

a three-phase permanent magnet synchronous electric generator comprising:

a fluid inlet configured to receive hydrogen gas at a first pressure,

a turbine wheel configured to expand the hydrogen gas and rotate in response to expansion of the hydrogen gas flowing into an inlet of the turbine wheel and out of the outlet of the turbine wheel,

a rotor coupled to the turbine wheel and configured to rotate with the turbine wheel,

a stationary stator, the three-phase permanent magnet synchronous electric generator to generate three-phase alternating current upon rotation of the rotor within the stator, and

a fluid outlet configured to output the hydrogen gas at a second pressure less than the first pressure; and

a power electronics system electrically connected to an electrical output of the three-phase permanent magnet synchronous electric generator and to receive three-phase alternating current from the three-phase permanent magnet synchronous electric generator.

2. The apparatus of claim 1, wherein fluid outlet is coupled to a fuel cell inlet of a fuel cell, and the fluid outlet configured to direct the hydrogen gas at the second pressure to the fuel cell.

3. The apparatus of claim 1, wherein the power electronics is electrically coupled to the fuel cell, and wherein the power electronics is configured to condition the three-phase alternating current to have a frequency and amplitude compatible to power the fuel cell.

4. The apparatus of claim 1, wherein fluid outlet is coupled to a gas turbine inlet of a gas turbine, and the fluid outlet configured to direct the hydrogen gas at the second pressure to the gas turbine.

5. The apparatus of claim 1, wherein:

the fluid inlet is configured to receive hydrogen gas at the first pressure from a trailer container; and

the fluid outlet is configured to output hydrogen gas at the second pressure to a compressor of a hydrogen gas storage facility.

6. The apparatus of claim 5, wherein the power electronics is electrically coupled to the compressor, and wherein the power electronics is configured to condition the three-phase alternating current to have a frequency and amplitude compatible to power the compressor.

7. The apparatus of claim 1, wherein:

the fluid inlet is configured to receive cooled heat exchange fluid at the first pressure from a first heat exchanger device hydrogen liquefaction system; and

the fluid outlet is configured to output expanded heat exchange fluid at the second pressure to a second heat exchanger of the hydrogen liquefaction system.

8. The apparatus of claim 7, wherein the power electronics is electrically coupled to one or more compressors of the first or second heat exchanger, and wherein the power electronics is configured to condition the alternating current to have a frequency and amplitude compatible to power the one or more compressors.

9. The apparatus of claim 7, wherein the power electronics is electrically coupled to one or more compressors of a pre-cooling heat exchanger of the liquefaction system, and wherein the power electronics is configured to condition the three-phase alternating current to have a frequency and amplitude compatible to power the one or more compressors.

10. The apparatus of claim 1, wherein the power electronics comprises a variable speed drive connected to the electrical output of the three-phase permanent magnet synchronous electric generator, the variable speed drive to convert the three-phase alternating current received from the three-phase permanent magnet synchronous electric generator into three-phase alternating current compatible with a power grid.

11. The apparatus of claim 10, wherein the variable speed drive comprises:

a rectifier to receive three-phase alternating current from the three-phase permanent magnet synchronous electric generator and convert the three-phase alternating current into direct current; and

an inverter to receive direct current from the rectifier and convert the direct current into an alternating current comprising an amplitude and frequency compatible with the power grid.

12. The apparatus of claim 1, wherein the electric generator comprises a three-phase electrical output, and wherein the brake resistor assembly comprises a brake resistor in series with each phase of the electrical output.

13. A method comprising:

receiving hydrogen gas at a first pressure into a turbine wheel of a three-phase permanent magnet synchronous electric generator, the hydrogen gas being received at a first pressure into the turbine wheel causing the turbine wheel to rotate and causing the hydrogen gas to expand;

causing a rotor to rotate within a stator of the electric generator by rotation of the turbine wheel;

generating three-phase electrical current by the three-phase permanent magnet synchronous electric generator by rotation of the rotor within the stator;

directing three-phase electrical current generated by the three-phase permanent magnet synchronous electric generator to a power electronics; and

outputting hydrogen gas at a second pressure, the second pressure less than the first pressure.

14. The method of claim 13, further comprising outputting the hydrogen gas at the second pressure to a fuel cell.

15. The method of claim 13, further comprising conditioning, by the power electronics, the electrical current to be compatible with powering the fuel cell; and directing the conditioned electrical current to the fuel cell.

16. The method of claim 13, further comprising:

receiving the hydrogen gas at the first pressure from a trailer container; and

outputting the hydrogen gas at the second pressure to a compressor at a hydrogen gas storage facility.

17. The method of claim 16, further comprising conditioning, by the power electronics, the electrical current to be compatible with powering the compressor.

18. The method of claim 13, further comprising:

receiving cooled heat exchanger fluid at the first pressure from a first heat exchanger of a hydrogen liquefaction system; and

outputting expanded heat exchanger fluid at the second pressure to a second heat exchanger the hydrogen liquefaction system.

19. The method of claim 18, further comprising conditioning, using power electronics, the electrical current to have a frequency and amplitude compatible to power one or more compressors of the hydrogen liquefaction system.

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